CoCO2

Prototype system for a
Copernicus CO_2 service

Analysis of the potential of IoT measurements

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Luca Cerato

Co-ordinated by
ECMWF

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1 Executive Summary

The use of Internet of Things (IoT) and low cost sensors have been evaluated and tested. Delays and limitations due to the COVID pandemic lockdown, crisis in the semiconductors and sensors construction and availability, together with some legal and administrative limitations in the installation of sensors on the buildings didn't allow to obtain a final answers and valid results. However different prototypes have been designed, tested and prepared and they are currently running and collecting data that however will produce results only after the end of the project.

2 Introduction

The need of an extensive monitoring network and the high heterogeneity in the urban environment would require the development of a large network that should allow the recording and transmission of a high volume of data. The potential use of Low Cost solutions for the monitoring of greenhouse gases in urban areas through the use of open hardware and low cost sensor systems (Internet of Things – IoT), which can be considered an environmentally-friendly technology, requiring a minimal energy intake and small size, needs to be tested because it would allow a high spatial distribution of monitoring points in the complex urban environment. The collection and processing of environmental data, their management and analysis would support the monitoring effort but also have a potential use and dissemination toward community, society and businesses, also using platforms and apps for real-time monitoring and information.

The quality of the measurements performed by these IoT sensors is however low and even not comparable with the high-quality measurements performed in large Infrastructure like ICOS and it is therefore necessary to evaluate their performances, evaluation of calibration techniques and possible data correction and processing. The focus of the activities has been focused on the CO2 concentrations measurements but also the possibility to measure fluxes have been tested.

3 Low Cost sensors to measure CO$_2$ concentration

The first step of the activities has been researching the market to find the best solution for our needs. The low-cost sensors, that measure CO2 concentration, can not be used directly in outdoor environments due to the exposure of their electronic components. Therefore, we focused on other aspects of the sensor, such as its accuracy, precision, and sample rate. The list and a brief description of the sensors evaluated in the laboratory is the following:

- SenseAir S8 sensor, useful for continuous sampling, can also sample at 2Hz, but a sample rate of a few minutes is recommended. Senseair produces an extremly low power CO2 sensor called LP8 with characteristics very close to the S8.
- K30 by SenseAir, has been demonstrated to follow the CO2 concentration patterns measured by standard equipment, but it is not possible to sample with frequencies higher than 1 Hz. The K33 by SenseAir, compared to the K30, the has an integrated humidity sensor and a temperature sensor. However the K33 is not recommended for sampling with sample rates lower than 30 seconds.
- SCD30 Sensirion, it is possible to identify it with an intermediate sensor between the K30 and the K33. Like the K33, the SCD30 has a temperature and humidity sensor on the same PCB, moreover it has an acquisition frequency of about 2 Hz much closer to the behavior of the K30.

- SprintIR-W by GSS (Gas Sensing Solution) is the most interesting of the Low Cost sensors for CO2 concentration. The most important element of the SprintIR-W sensor is its sampling rate of 20Hz.

The technical characteristics of the sensors considered are reported in Table 1. As it is possible to see there is a large heterogeneity in terms of information provided by each single company/model, with some of the data only generic or missing. This calls the attention to the need of a laboratory test and evaluation before the use in field.

Table 1: Characteristics of the Low Cost Sensor for CO2 concentration tested

Technical sheet	K30 (FR)	K33 (LP T/RH)	SCD30	S8(LP)	SprintIR-W
Company	Senseair	Senseair	Sensirion	Senseair	Gas Sensing Solutions
Accuracy	±30 ppm ±3% of reading	±30 ppm ±3% of reading	±(30 ppm + 3%) at 400-10.000 ppm	±40 ppm ±3% of reading	±70ppm ±5% +~0.1% per °C
CO_2 RMS Noise	Digital filter setting 16ppm				
Accuracy drift over lifetime			± 100 ppm		
Repeatability		±20 ppm ±3% of reading	± 10 ppm		±70ppm, +5%(@25°C)
Measurement range (ppm CO_2)	0-5.000	0-5.000	400– 10.000	0-10.000	5%, 20%, 60%, 100%
Operating principle	NDIR	NDIR	NDIR	NDIR	NDIR
Sampling method		Diffusion			
Temperature compensation	Yes	Yes	Yes	Yes	Yes
Humidity compensation	Yes	Yes	Yes	Yes	Yes
Time to Valid Measurement After Power-On					1.2sec
Response time (T1/e)	20 sec diffusion time	<1min, 30s measurement period	20s	2 minutes	20ms
Operating Ambient Pressure Range					500mbar to 2bar
Working pressure					0.3bar
Pressure dependence		+1.6% reading per kPa			
Rate of measurement	0.5Hz	Default 30s	2s	4s	20Hz
Communication interface	I2C, UART	UART, analogic, I2C	UART, I2C	UART	UART
Baud rate				9600	
Power supply	4.5 – 14 V DC	4.75 - 12 V DC	3,3-5,5 V DC	4,75-5,25 V DC	-0.3 to +6.0V DC
Current Consumption	40mA average <300 mA peak power (during IR lamp start-up, the first 50msec)	A 1.5mA 0.75mA 86 µA	*Measurement interval* 30s 60s 15min	Update interval 2s: 19 mA During measurement 75 mA	18mA (Average)

		52 µA	60min		
Peak current		<300mA		300mA	
Warm Up time to spec precicsion	1min	<3min, 30s measurement period			
Dimensions	51 x 58 x 12 mm	51.15 x 50.80 x 11.80 mm	23x35x7 mm	33.9 x 19.8 x 8.7 mm	42.4 x 25 x 37 mm
Weight				<8g	7g
Temperature measurement range	0 – 50 °C	0 – 50 °C	0 a +50 °C		0 a +50 °C
Temperature stability			± 2.5 ppm / °C		
Temperature measurement accuracy		*See* ***Errore. L'origine riferimento non è stata trovata.***			
Operation humidity range	0-95%	0-80%	0-80%	0-85%	0-95%
RH accuracy		-5 – 5% within range 0-50%RH			
		-5 – 15% within range 50-100%RH			
CO2 operating temperature /humidity range		*See* ***Errore. L'origine riferimento non è stata trovata.***			
Sensor life expectancy	> 15 years	> 15 years	> 15 years	> 15 years	> 15 years

3.1 Details on sensors evaluated.

In this section more details and the schemes of the sensors tested are reported, including where available the results of the factory calibration and performance reports. The information provided are the one coming from the companies and not verified in the context of the project, however are the information used to select the sensors to be used and evaluated in the tests.

3.1.1 K30 Senseair Sensor

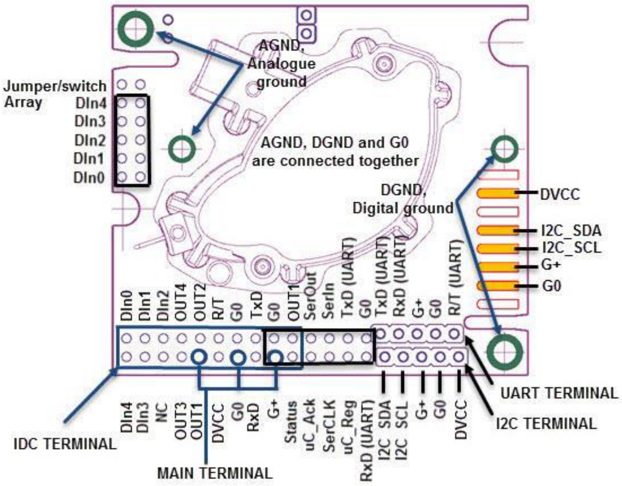


Figure 1. Senseair K30 PCB overview

The Senseair K30 sensor is produced in different versions, with differences in the range of CO2 concentration measured and the response time (Table 2). For the tests in the context of the COCO2 project the K30 FR sensor was selected and used.

Table 2. K30 Sensair Variation

Product number	Product	Features
030-8-0006	Senseair K30	Standard configuration (0 to 5,000 ppm, 20 s diffusion time)
030-8-0011	Senseair K30 10,000	Measurement range up to 10,000 ppm CO2
030-8-0015	Senseair K30 5,000	Measurement range up to 5,000 ppm CO2
030-7-0001	Senseair K30 3%	Measurement range 0 to 3%vol
030-8-0010	Senseair K30 FR	030-8-0010

3.1.2 K33 LP T/RH Senseair Sensor

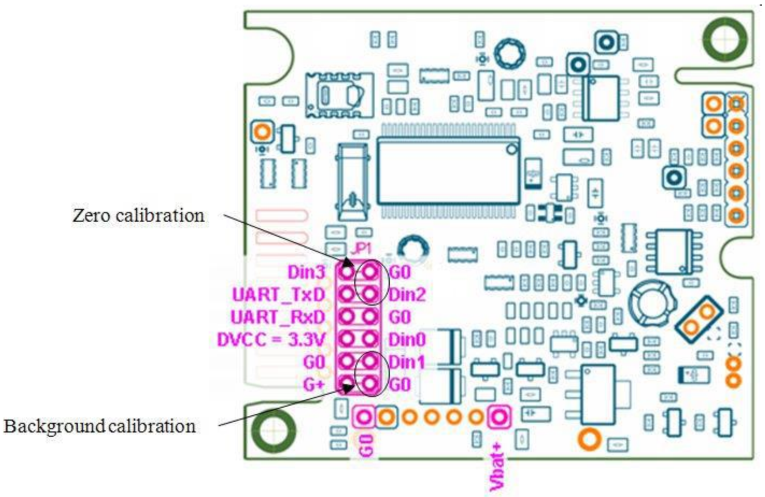


Figure 2. Senseair K33 LP T/RH PCB. Source. Source: Product Specification Senseair K33 LP T/RH Sensor and OEM Platform. Document PSP0121 Rev 8

K33 LP T/RH is a low-power module that measures CO2, temperature and humidity. The adjustable measurement interval results in average current that can be reduced to less than 52 µA (one measurement every 60 minutes). Two different models exists (Table 3).

Table 3. K30 Sensair Variation

Product number	Product	Features
033-8-0008	Senseair LP T	Low power sensor core for CO$_2$ and temperature measurement
033-8-0009	Senseair LP T/RH	Low power sensor core for CO$_2$, temperature and RH measurement

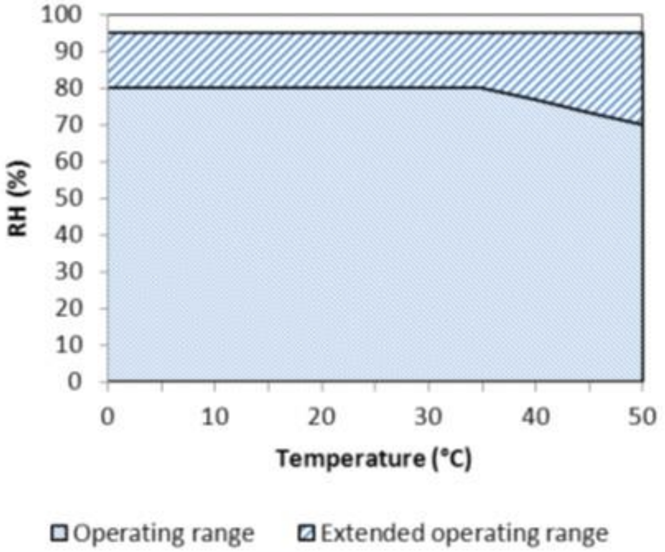


Figure 3. CO2 operating temperature/humidity range. Source: Product Specification Sensair K33 LP T/RH Sensor and OEM Platform. Document PSP0121 Rev 8

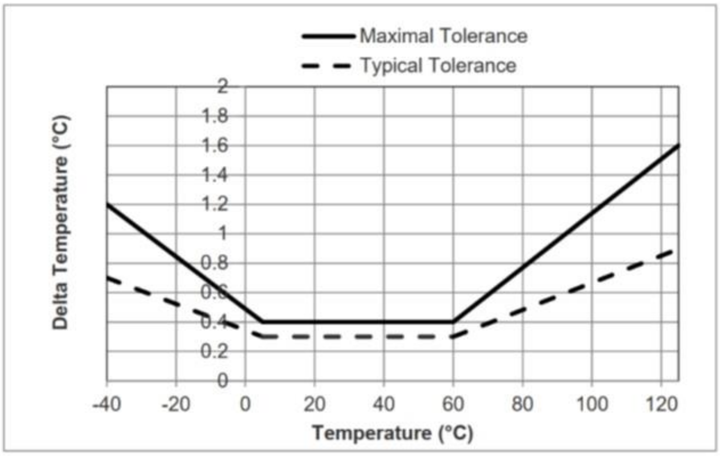


Figure 4. Temperature measurement accuracy. Source: Product Specification Sensair K33 LP T/RH Sensor and OEM Platform. Document PSP0121 Rev 8

The K33 LP T/RH is provided by an IIR filter (Infinite Impulse Response filter). The IIR filter is a type of digital filter used in the Senseair K33 LP T/RH sensor to process temperature and relative humidity (RH) data. The IIR filter is a filter that uses feedback, ie the output of the filter is also used as an input, creating a feedback loop.

This type of filter is used for filtering analog or digital signals and allows to obtain a customizable frequency response. Furthermore, the IIR filter has the characteristic of being continuous-time, ie the output depends on the state of the filter in a given instant of time and on the previous state.

In the K33 LP T/RH sensor, the IIR filter is used to filter out unwanted variations in temperature and relative humidity and ensure stable and accurate measurement. In particular, the IIR filter is used to remove the higher frequency components, which can be caused by rapid changes in temperature and relative humidity.

The use of the IIR filter in the Senseair K33 LP T/RH sensor ensures accurate and stable measurement of temperature and relative humidity, making it suitable for a wide range of applications including air quality monitoring and environment control.

3.1.3 SCD30 Sensirion

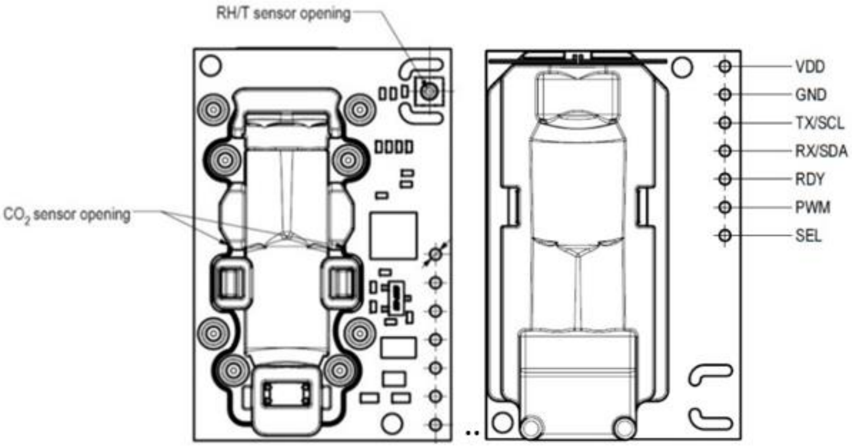


Figure 5. SCD30 CO2 sensor - sensor on left, pinout on right

The response time of the SCD30 CO2 output signal is affected significantly by the sampling interval. The follow plot shows the CO2 output signal for different sampling intervals after a sudden increase of the CO2 concentration done officially by the Producer of the sensor.

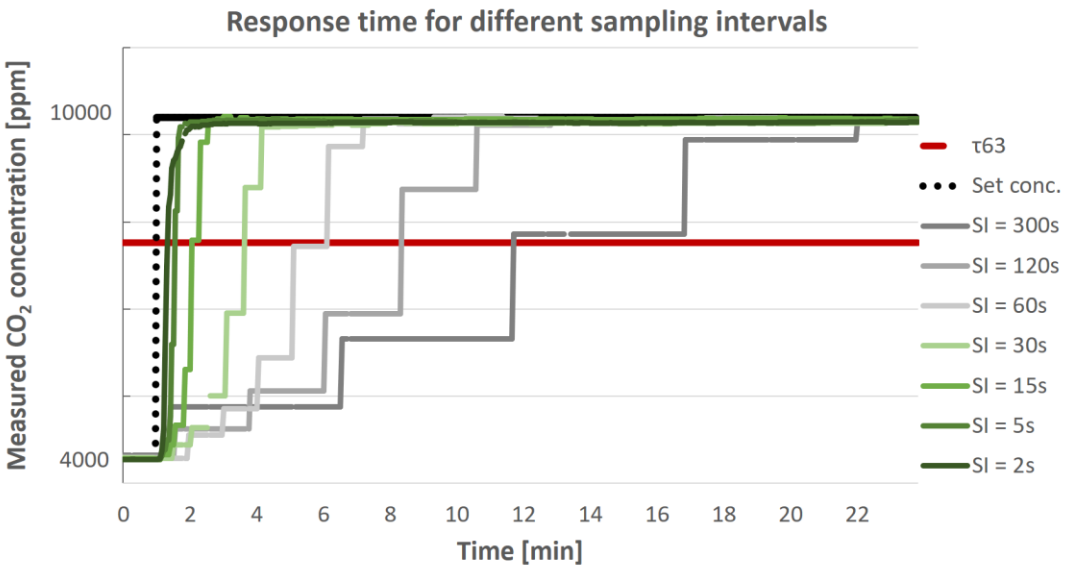


Figure 6.CO2 output signal evolution of SCD30 sensor with different sampling intervals (SI) after a rapid change of the CO2 concentration. Source: Sensirion Application Note SCD30 CO2 sensor.

The red line indicates the τ63 threshold and the dotted black line indicates the CO2 concentration set point. While the response time is very low (< 40 sec.) for small sampling intervals (2 sec and 5 sec), the response time for high sampling intervals (> 60 sec) takes several minutes.

3.1.4 S8 LP Senseair

The S8 Senseair sensor is produced in different versions that have different ranges, resolutions and structure. In this activity the S8LP was selected.

Table 4. S8 SenseAir CO2 sensor - Variations

Product number	Product	Features
004-0-0050	S8 2%	For connection by pin headers
004-0-0013	S8 Residential	For connection without pin headers
004-0-0017	S8 5%	For connection by pin headers
004-0-0053	Senseair S8 LP	For applications where both energy consumption and accuracy are critical factors
030-8-0010	Senseair K30 FR	030-8-0010

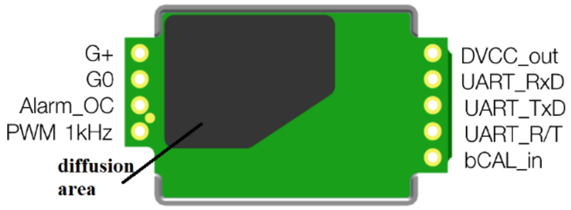


Figure 7. S8 pinout and diffusion area

3.1.5 SprintIR-W GSS

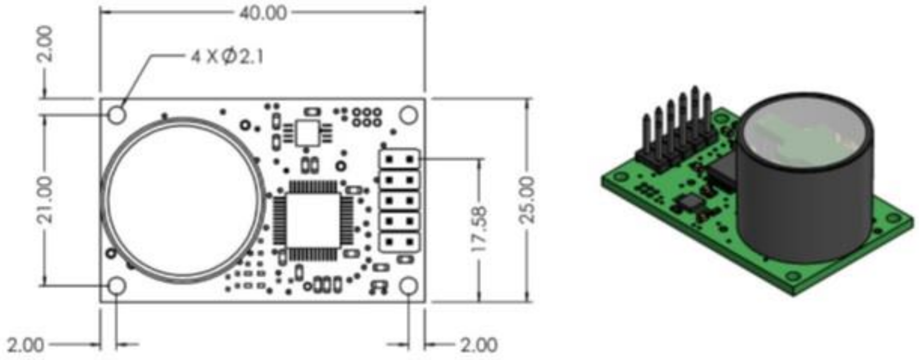


Figure 8.SprintIT-W with Membrane Cover

The CO2 gas chamber is illuminated with a nominal 4.25µm wavelength LED and the signal received using a photodiode. The signal from the photodiode is processed and filtered by the sensor to remove noise and provide an accurate CO2 reading. High frequency noise coming from the sampling process is removed using a proprietary lowpass filter. The digital filter setting can be varied, allowing the user to reduce measurement noise at the expense of the measurement response time.

The ideal digital filter setting is application specific and is normally a balance between CO2 reading accuracy and response time. The SprintIR-W sensor will also output the raw unfiltered CO2 measurement data. This data can be post processed using alternative filter algorithms. The graph in Figure 9 shows the effects of the filter on the CO2 measurement data. The unfiltered output is shown in orange and the filtered output shown in blue.

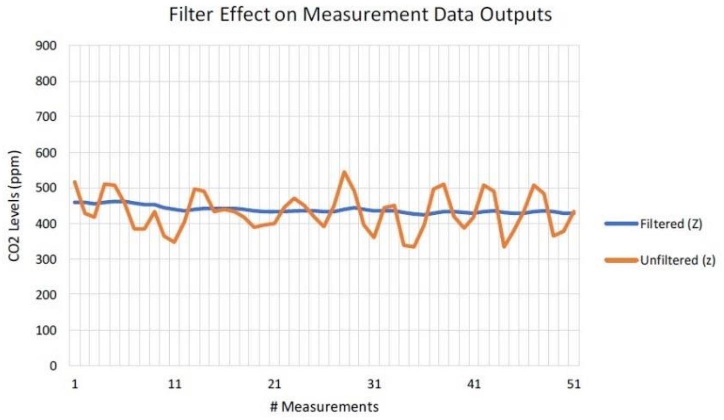


Figure 9. SprintIR-W Filter Effect on measurement Data Outputs. Source: GSS(Gas Sensing Solutions) SprintIR-W Data sheet

Figure 10 shows the effect of the filter on response times. Increasing the filter setting increases the measurement output response time. T90 is the time to 90% of reading. The SprintIR-W takes 20 readings per second. The flow rate was set at 0.2l/min. Sampling noise is progressively reduced with higher digital filter settings. It is recommended the user sets the highest value digital filter setting without compromising the required flow rate (Table 5).

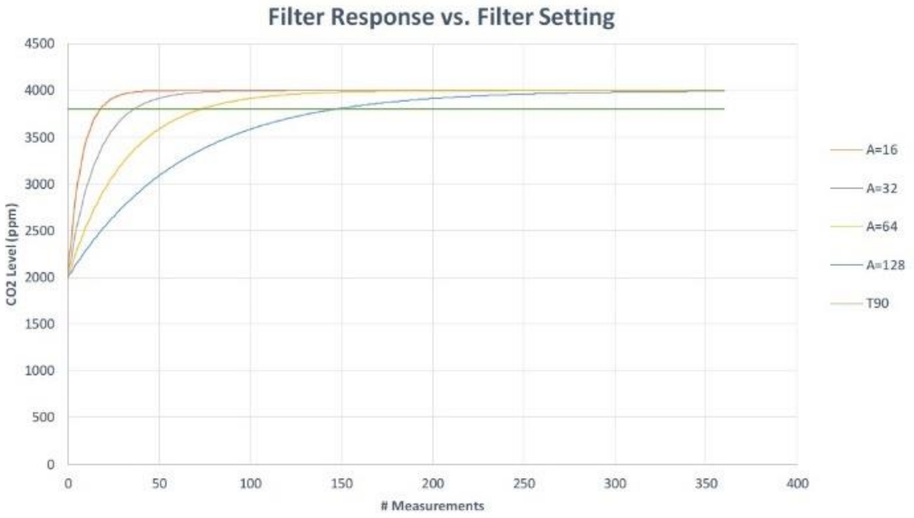


Figure 10. SprintIR-W Filter Response vs. Filter Setting. Source: GSS(Gas Sensing Solutions) SprintIR-W Data sheet

Table 5. SprintIR-W - Flow Rate Recommended Digital Filter Setting

Flow Rate	Recommended Digital Filter Setting ‘a’
0.1litre/minute	64
0.5litre/minute	32
1litre/minute	16
5litre/minute	8

For the SprintIR-W, GSS provides an altitude compensation methods that can be consulted directly on the Datasheet, including the complete table that below is shown partially in Table 6.

Table 6. S8 SenseAir CO2 sensor - Variations

Altitude(m)	*Pressure(mbar)*	CO2 Measurement Change (%)	Compensation Value
0	*1.013*	*0*	*8.192*
153	*995*	*3*	*8.398*
305	*977*	*5*	*8.605*
…	…	…	…

4 Sensors laboratory test setting

In order to have a reference value for the IoT sensors evaluation, high quality and fully calibrated CO2 gas analyzers have been used (LICOR LI-7200 and LI7500A). The reference sensors were mounted on a wooden frame constructed to maintain the sensors during the test.

To test the sensors, self-made circuit boards (CBs) were created to connect the sensors to the microcontroller. The communication from the sensors to the microcontroller was mainly through the Universal Asynchronous Receiver/Transmitter (UART) and Inter-Integrated Circuit (I2C) protocols. The data collected from the sensors were saved on an SD card.

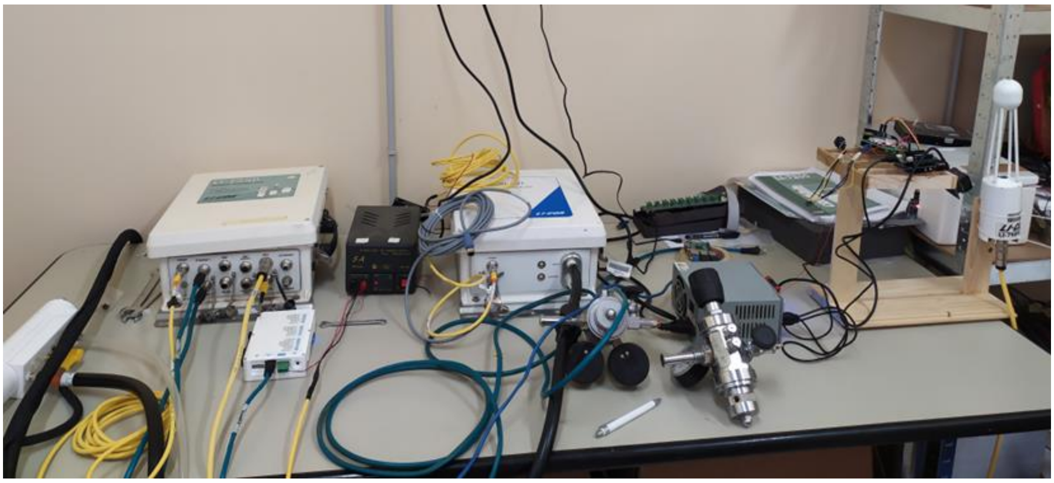


Figure 11. Full setting Test reference and Low Cost sensors with LI-7500A on the right

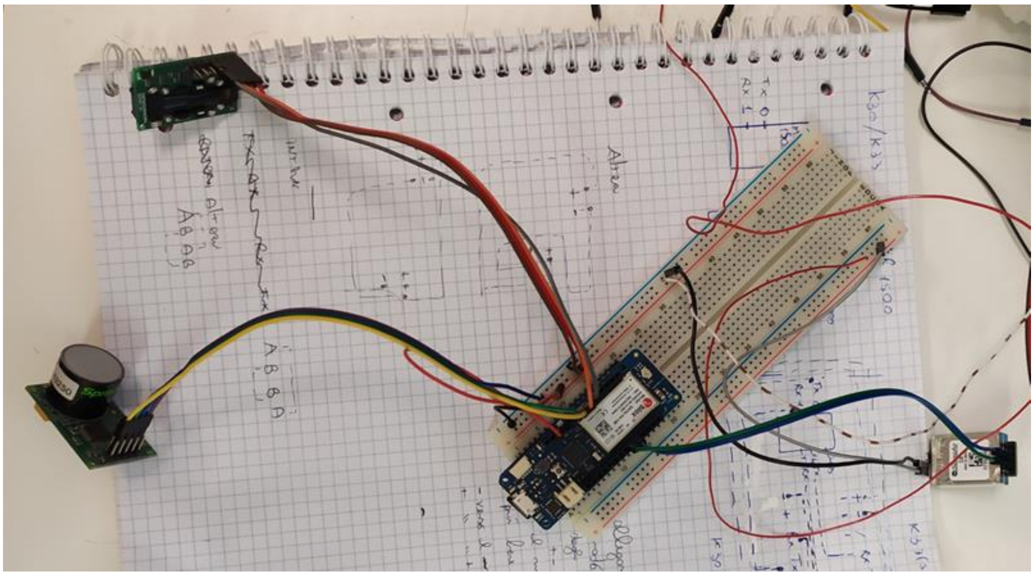


Figure 12. First Test -S8-SCD30-SprintIR-MKR1500 NB IoT microcontroller -saving data on SD card

In the initial phase, the most suitable and feasible communication protocols for each sensor were analyzed and selected. Subsequently, a proper circuit connection was established with the microcontroller. Finally, the code was written and developed for reading the sensors and writing their data to an SD card.

In the subsequent step, dedicated circuit boards were created for the various sensors that could manage the various voltage levels required for the proper functioning of the microcontroller and the sensors. Additionally, the sensors and the board were designed to be easily extracted and repositioned by an operator with minimal prior experience in electronics, with only minimal precautions. Furthermore, the code developed allows for the elimination of one or more sensors by commenting out the dedicated part, without requiring any further changes to the code or the electronic circuit.

Figure 13. PCB -S8-SCD30-SprintIR-MKR1500 NB IoT microcontroller saving data on SD card

Figure 14. K30-K33- MKR1500 NB IoT - top view

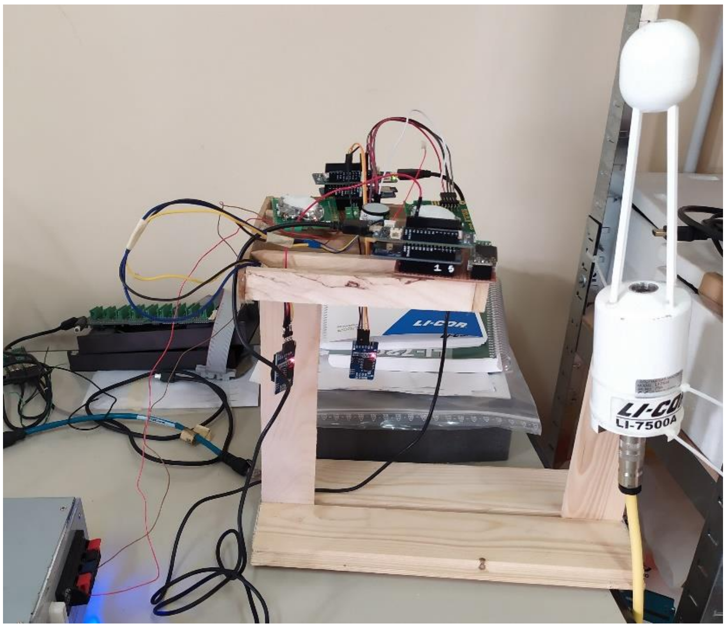


Figure 15. Sensor’s Test on the wood frame- Low Cost sensors on the left and Reference sensor on the right

5 Ventilation ducts monitoring

The hot wire anemometer is a device that can be placed within ventilation ducts to measure the velocity of air. When used in conjunction with a gas concentration sensor, it can evaluate the gas flow rates of a specific species. The sensor can be placed at the exit of the roof vent to measure the flow rate of a specific gas. Developing different solutions, this analysis can be extended to all the sewer system, until the waste water treatment.

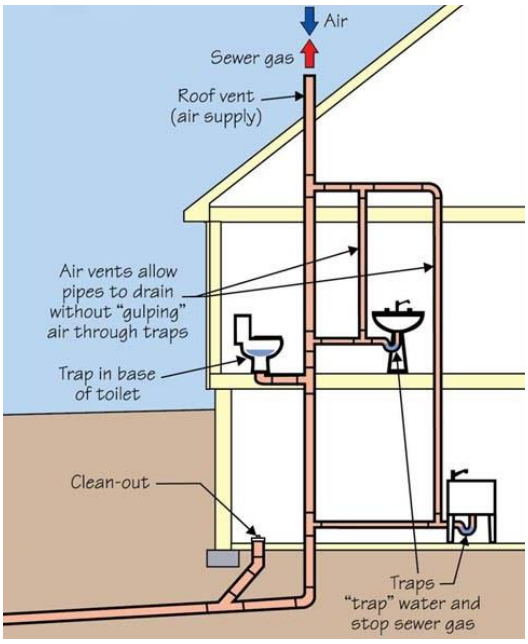


Figure 16. Drainage, Waste and Vent System - Pumpling Vent Diagram. Source: Tom Feiza Mr Fix-It Inc

A hot wire anemometer is a device used for measuring the velocity of a fluid, typically air. The principle behind its operation is rooted in the physical properties of a heated wire exposed to the fluid flow. When an electric current passes through a wire, it heats up due to the electrical resistance of the material. In the case of a hot wire anemometer, the wire is maintained at a constant temperature above the ambient level. As the fluid flows over the wire, it carries away heat, causing the wire to cool down. The amount of cooling is directly proportional to the fluid velocity.

This change in temperature is measured, and by applying the principles of convective heat transfer and fluid dynamics, the fluid velocity can be accurately determined. This method provides a reliable and efficient means of measuring airflow in various applications, from environmental monitoring to industrial processes.

The purpose of the test was to understand the behavior of the hot wire anemometer inside the duct. To install the sensor a small incision was made to insert only the anemometer filament, leaving the electronic components outside in order to minimize the alteration of the measurement due to the positioning of the sensor.

The sensor was connected to the analog pins of an Arduino nano RP2040. On the microcontroller was uploaded a code able to receive and convert the signal from the sensors into understandable data. The duct of known dimensions was open on only one side. On the other side a fan was installed which pushed the air out of the duct generating a suction flow from the open side.

The variation of the flow speed was obtained by varying the fan's power supply voltage and therefore its rotation speed.

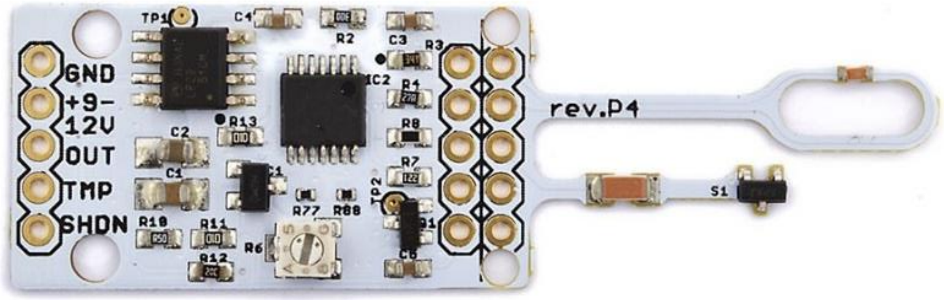


Figure 17. Hot wire anemometer -rev-p

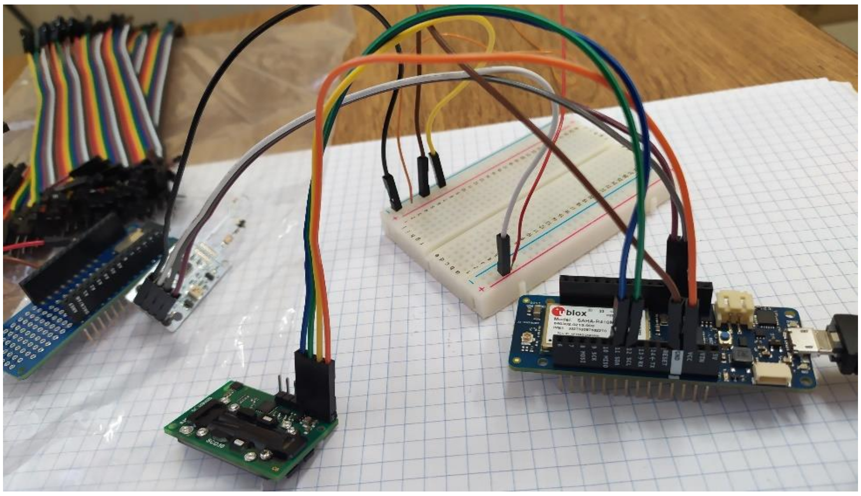
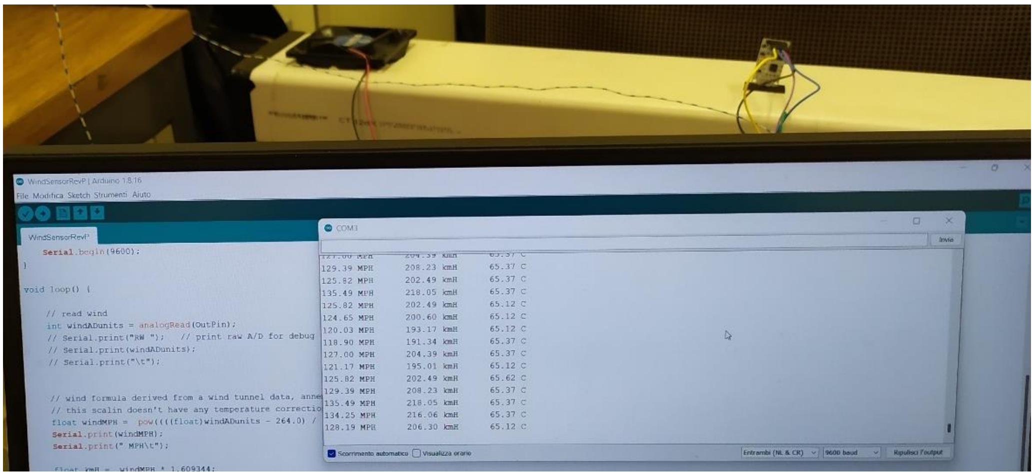


Figure 18. First Test - SCD30 - Hot wire anemometer -rev-p - SprintIR-MKR1500 NB IoT microcontroller



```
  Serial.begin(9600);
}

void loop() {

   // read wind
   int windADunits = analogRead(OutPin);
   // Serial.print("RW ");   // print raw A/D for debug
   // Serial.print(windADunits);
   // Serial.print("\t");


   // wind formula derived from a wind tunnel data, anne
   // this scalin doesn't have any temperature correctio
   float windMPH =  pow((((float)windADunits - 264.0) /
   Serial.print(windMPH);
   Serial.print(" MPH\t");

   float kmH =  windMPH * 1.609344;
```

```
129.39 MPH      208.23 kmH      65.37 C
125.82 MPH      202.49 kmH      65.37 C
135.49 MPH      218.05 kmH      65.37 C
125.82 MPH      202.49 kmH      65.12 C
124.65 MPH      200.60 kmH      65.12 C
120.03 MPH      193.17 kmH      65.12 C
118.90 MPH      191.34 kmH      65.37 C
127.00 MPH      204.39 kmH      65.37 C
121.17 MPH      195.01 kmH      65.12 C
125.82 MPH      202.49 kmH      65.62 C
129.39 MPH      208.23 kmH      65.37 C
135.49 MPH      218.05 kmH      65.37 C
134.25 MPH      216.06 kmH      65.37 C
128.19 MPH      206.30 kmH      65.12 C
```

Figure 19. Hot wire anemometer -rev-p _Testing Evaluation and Coding

Developing electronic prototypes is a complex and time-consuming process that requires with challenges in both the sensors' setup and acquisition and their actual performances. Between the second half of 2021 and 2022, several electronic prototypes were developed, however they could not be developed further due to their performances, the expected time for a full development (well beyond the time of the project) and the authorizations needed for their installation on the roofs.

6 Single point measurements and profiles

A punctual station (single sensor) was created using low-cost elements without any moving parts (no fan). A RPI-Zero 2W (self-founded) was selected for its ability to connect to the internet and send data. The data are saved in a file and sent every 5 minutes to a server where it is possible to remotely connect and download or view the data. The absence of a fan does not allow for rapid air variation within the volume of the junction box. To facilitate and speed up the exchange of air, two open pipes were positioned in front of the sensor's sensing texture. Additionally, the lower part of the tube exposed to the environment was provided with a fiberglass mesh to allow the passage of air while reducing the risk of insect entry. This allows for the recirculation of air, which does not necessarily have to be instantaneous since the sensors are sampled once every 30 seconds.

An integrated SD card on the board allows to acquire data continues and save even in the absence of momentary connectivity and the data are then sent as soon as connectivity becomes available again. This system also allows for remote upload and modification of the code and settings that manage the sensor and connectivity setup.

6.1 Potential applications

This system can be used both indoor and outdoor. More specifically in the project two outdoor applications have defined:

- Vertical profiles for CO2 storage: positioning the sensor on various sides and levels of the building to measure changes in concentrations of CO2 at different levels, starting from street level and reaching levels higher than the building, where atmospheric mixing is expected. This could provide information about the storage flux, relevant when the eddy covariance technique is used and also very heterogeneous (spatially) in urban environments.

- Specific analysis of vertical profile heterogeneity on a single building: the activity was designed to understand how wind speed and direction can influence the concentration of CO2 on the various sides of the same building. This will provide important information on how many vertical profiles would be needed to correctly characterize the storage flus in eddy covariance applications in urban environments.

6.2 Prototypes designed and under test

Two different setups have been created: one with two redundant K33 sensors in order not only to have a backup system but also to work on the average between the two sensors and reduce the random uncertainty (Figure 20).

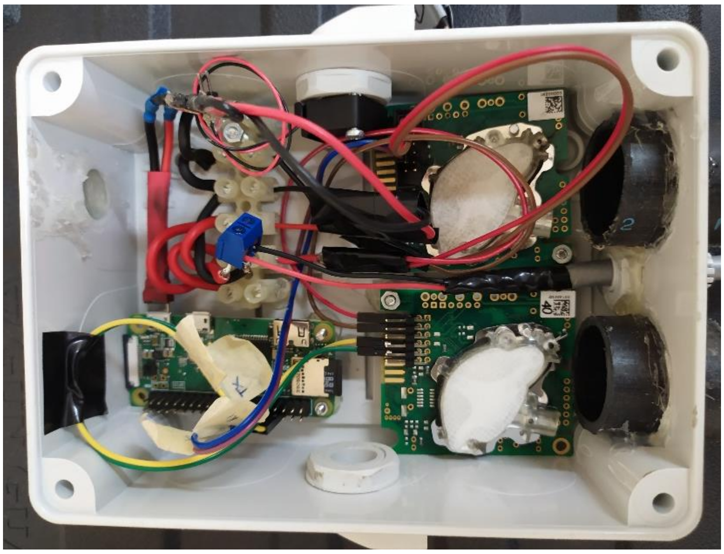


Figure 20Redundant system with two K33 sensors

An alternative, more economical stations (economically and in terms of energy consumption) was then created, using only one K33 sensor and improved and optimized cables connection. A separator was also added to reduce the volume of the sampled air, which also helps to protect the micro-computer from the exposure to potentially high humidity air (Figure 21).

Figure 21. station with single K33 sensor and components separator

Multiple single point stations, with one and two (redundant) K33 sensors were created and positioned at two different levels of a University building, on different building sides and with an anemometer to monitor also wind speed and direction (Figures 22 and 23).

Figure 22. Single K33 punctual station installed on the balcony

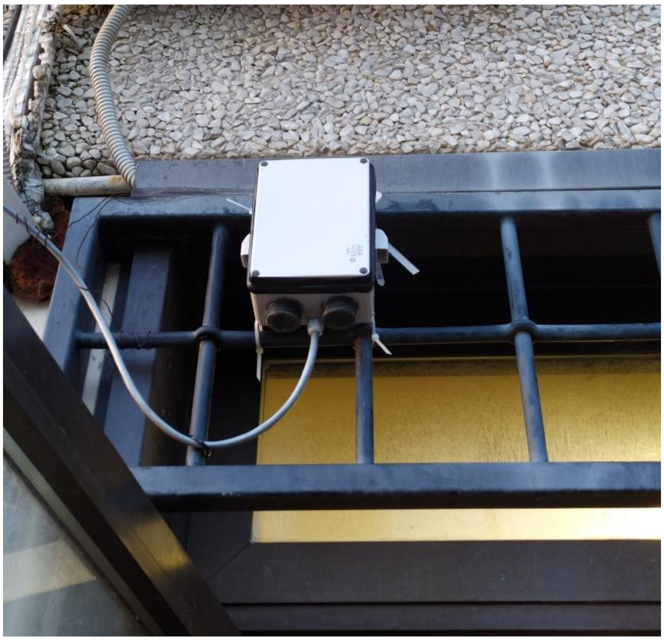


Figure 23. Redundant K33 punctual station installed

7 Eddy covariance

Eddy covariance is a sophisticated technique widely employed in environmental science, particularly in the study of ecosystem fluxes. This method allows to measure exchange of gases, such as carbon dioxide and water vapor, between the Earth's surface and the atmosphere. Eddy covariance relies on high-frequency measurements of wind speed and gas concentration to calculate fluxes. This technique plays a crucial role also in the monitoring of CO2 emissions or exchanges in urban environments being the only method able to record fluxes directly.

The basic setup of an eddy covariance system includes a sensor to measure wind speed and direction (such as an anemometer), a sensor to measure the concentration of the gas of interest (such as a gas analyzer), and a data logger to record the data. The system is typically installed at a height of 2-20 meters above the surface and the data is recorded at high frequency (typically at least 10 Hz).

The frequency at which data is collected in an eddy covariance system is an important factor in determining the accuracy of the measurements. A higher measurement frequency allows for a more detailed representation of the turbulent fluctuations in wind speed and gas concentration.

It is important to note that the measurement frequency is just one factor that affects the accuracy of the eddy covariance measurements, other factors such as the quality of the equipment, the location of the measurement, and the processing and analysis of the data also play a role.

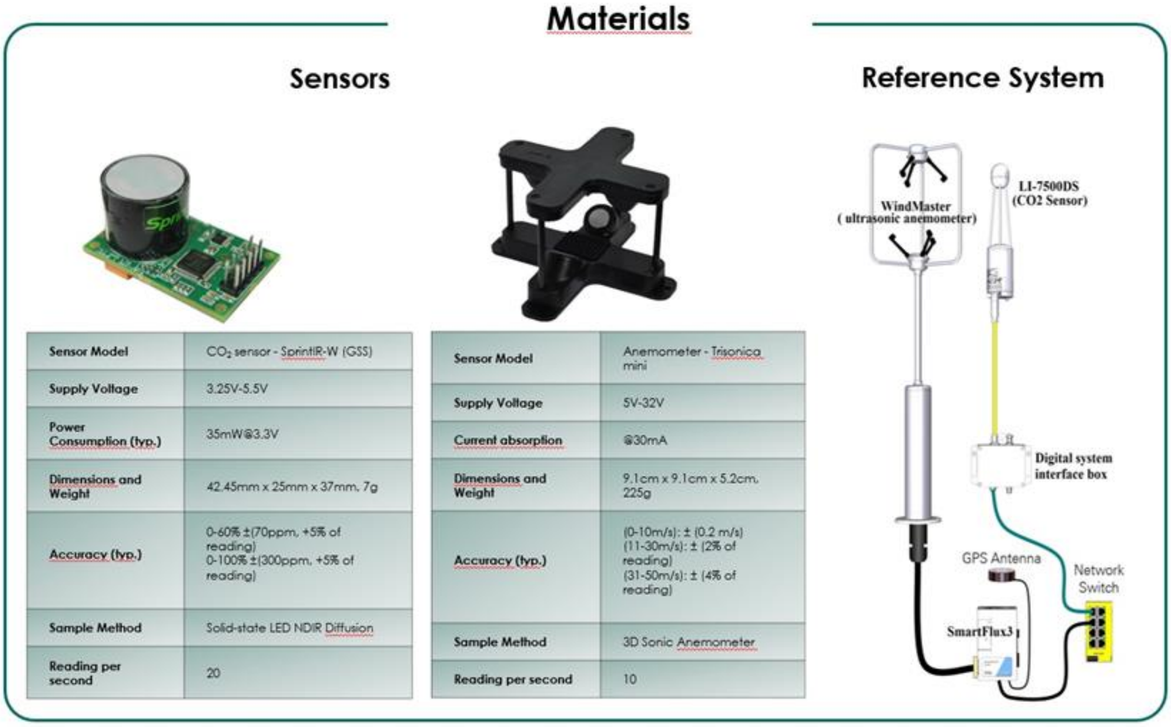
7.1 Evaluation of low cost solution for Eddy Covariance

Typically, a classic EC system costs tens of thousands of euros and therefore the accessibility to this technology could be limited in some users communities or countries, such as in developing countries or large scale applications. Technological development has also led to the production of sensors defined as Low Cost (LC). The application of this technology for the development of new EC LC system would increase the number of users and sites leveraging the costs related issues.

At the same time, the accuracy and precision of the LC sensors are not comparable with the standard EC systems and for this reason their usability in EC application and the related uncertainties are still not clear. The idea was to design and test an EC LC system including the comparison with a standard reference EC system. Although it is not expected to have results comparable with the standard systems, an EC LC could potentially be used in case of very large fluxes (possible in urban environments) in particular to compare temporal patterns and changes.

7.1.1 Low cost sensors selected

For the development and test of a EC LC system the two sensors selected, after the review of the technical characteristics and performances have been the SprintIR-W CO2 gas concentration sensor (already described in the first part of this document), and the Trisonica mini 3D anemometer, in particular the model TSM-PM that is designed to be controlled and acquired by both computers and microcontrollers (Figure 24).



Sensor Model	CO$_2$ sensor - SprintIR-W (GSS)
Supply Voltage	3.25V-5.5V
Power Consumption (typ.)	35mW@3.3V
Dimensions and Weight	42.45mm x 25mm x 37mm, 7g
Accuracy (typ.)	0-60% ±(70ppm, +5% of reading) 0-100% ±(300ppm, +5% of reading)
Sample Method	Solid-state LED NDIR Diffusion
Reading per second	20

Sensor Model	Anemometer - Trisonica mini
Supply Voltage	5V-32V
Current absorption	@30mA
Dimensions and Weight	9.1cm x 9.1cm x 5.2cm, 225g
Accuracy (typ.)	(0-10m/s): ± (0.2 m/s) (11-30m/s): ± (2% of reading) (31-50m/s): ± (4% of reading)
Sample Method	3D Sonic Anemometer
Reading per second	10

Figure 24. Overview of the sensors used and system

7.1.2 Low cost EC System

The unit for an application like the one proposed must be able to manage the sensors autonomously, equipped with a solar panel and batteries in the event of a temporary lack of external power, allowing continuous data sampling. On this basis a first prototype was designed, created and tested. The dimensions of the prototype are 19cm x 40cm x 8cm and a solar panel of dimensions 20 x 23cm x 2cm, for a total weight of less than 3kg.

This system uses the SprintIR-W 5% to measure CO2 concentration at a sampling frequency of 20Hz and the Trisonica mini sonic anemometer with a sampling frequency equal to 10Hz. The development required not only iterative laboratory tests and the development of dedicated electronics but also the writing of codes for managing the system board, reading the sensors and saving the acquired data.

The sensor's printed circuit board (PCB) was placed inside a junction box, with the membrane exposed to the environmental conditions. To prevent contact with water droplets, a cylinder was placed around the membrane. The cylinder allows the water to drain along it and fall to the ground (Figure 25 and 26)

Figure 25. SprintIR-W membrane exposed

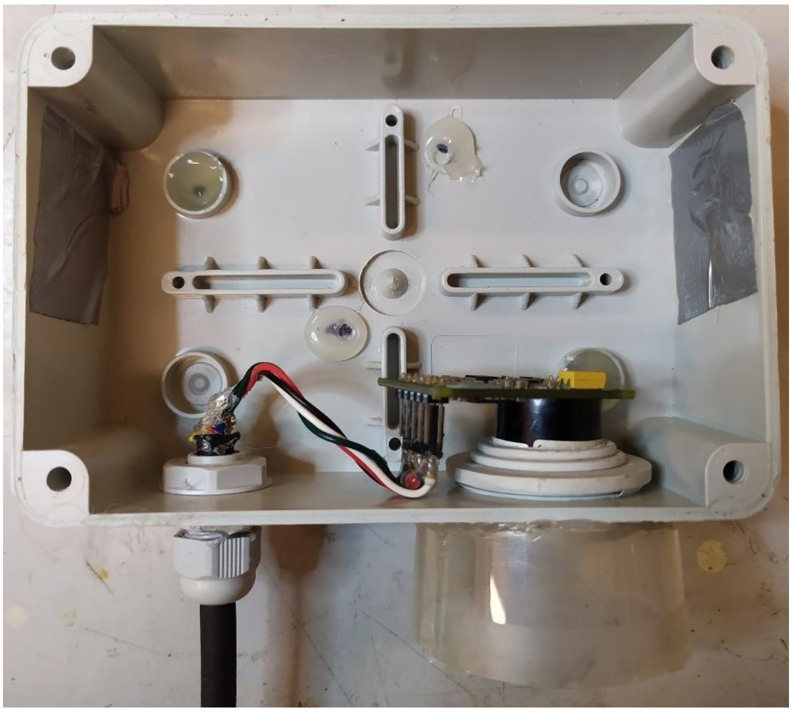


Figure 26SprintIR-W - electronics side and wiring in the box - membrane exposed with cylindric drop wall

Two files are produced through the microcontroller, one for the sensor for the CO2 concentration and one file for the data produced by the sonic anemometer. Each single file has a size of 1 Mb. The system (Figure 27) was installed in the test facility of the ICOS ETC, in parallel with a standard non-ICOS medium cost EC system (Figure 28).

Figure 27. Eddy Covariance Low Cost prototype

Figure 28. Installation of SprintIR and Trisonica with a standard EC system for reference

7.1.2.1 *Change of the acquisition system*

The Eddy Covariance Low Cost prototype version V2.0 uses the same sensors but the acquisition and management of data system have been changed, moving from microcontroller to field 12V Industrial computer, which is directly connected to the internet (Figure 29). The limitations in the microcontrollers in fact didn't allow a prompt and easy control and check of the EC LC system, including the possibility of a remote restart if needed.

Figure 29. ADVANTECH ARK-11 embedded computer

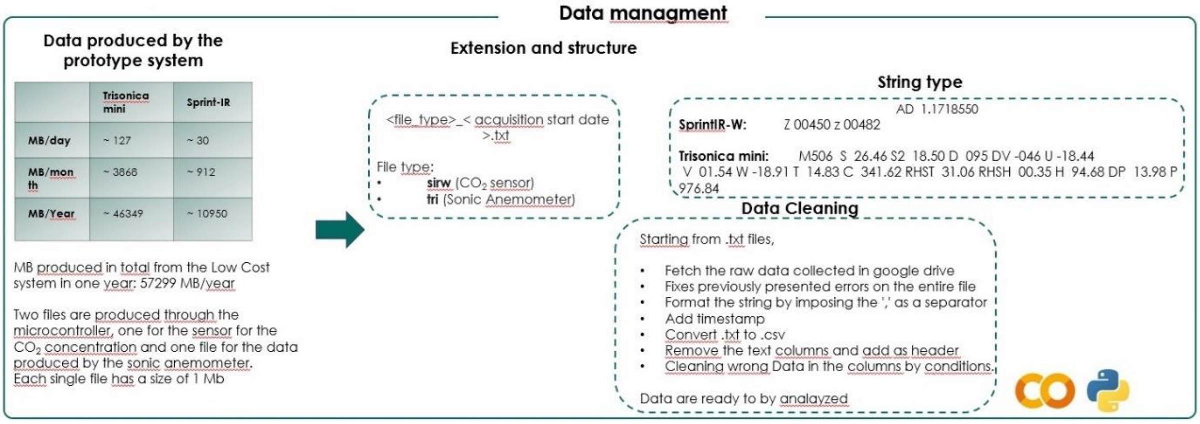
Additionally, a code has been developed that sends an email directly in case of an unexpected system restart. This allows the operator to remotely monitor the situation and perform useful operations for the control and management of the sensors. The station has also been configured to send data to an FTP server, which is also remotely accessible and from which files can be downloaded.

The ARK-11 computer is equipped with 4 USB ports and 2 RS-232 DB-9 ports. The two low-cost sensors communicate via the UART protocol, and an FTDI (UART to USB) converter is used to read the sensor data by the ARK-11 computer. FTDI chips are commonly used to convert UART signals to USB signals, allowing for easy communication between the sensor and the computer. The length of the wires used to connect the sensors to the FTDI converter can affect the quality of the signal, so both the sensors are connected with a wire length less than 2.5m. In this version of the prototype, the internal wiring of the Trisonica mini was changed to enable direct communication via UART at a fixed baud rate.

7.1.3 Data cleaning and processing

Data cleaning is an important step in data analysis that involves identifying and correcting errors in the data. Common errors in sensor data include missing values, incorrect values, and outliers. These errors can be caused by a variety of factors such as sensor malfunction, environmental factors, or human error. In case of Low Cost sensors this step is particularly relevant because of the quality of the measurements, the random errors and the possible biases and trends due to responses to temperature and humidity.

A specific Python script has been created on the Google Colab Cloud platform that, starting from the raw .txt files produced by the two sensors, retrieves raw data saved in Google Drive, corrects possible errors in the data acquisition, formats the string by imposing comma as a separator and adds the timestamp (Figure 30).



	Trisonica mini	Sprint-IR
MB/day	~ 127	~ 30
MB/month	~ 3868	~ 912
MB/Year	~ 46349	~ 10950

MB produced in total from the Low Cost system in one year: 57299 MB/year

Two files are produced through the microcontroller, one for the sensor for the CO$_2$ concentration and one file for the data produced by the sonic anemometer. Each single file has a size of 1 Mb

<file_type>_< acquisition start date >.txt

File type:
- **sirw** (CO$_2$ sensor)
- **tri** (Sonic Anemometer)

```
                              AD  1.1718550
SprintIR-W:        Z 00450 z 00482

Trisonica mini:      M506  S  26.46 S2  18.50 D  095 DV -046 U -18.44
 V  01.54 W -18.91 T  14.83 C  341.62 RHST  31.06 RHSH  00.35 H  94.68 DP  13.98 P
976.84
```

Starting from .txt files,

- Fetch the raw data collected in google drive
- Fixes previously presented errors on the entire file
- Format the string by imposing the ',' as a separator
- Add timestamp
- Convert .txt to .csv
- Remove the text columns and add as header
- Cleaning wrong Data in the columns by conditions.

Data are ready to by analayzed

Figure 30. Overview lo w cost sensor data management

8 Delays, issues and plan

The activity and the deliverable have been strongly affected by external factors that slowed down the development and test of the IoT sensors, not allowing to obtain the expected results. In particular the main issues encountered have been:

- COVID Pandemic and lockdown, that didn't allow the access to the laboratory, slowing down the preparation of the prototypes and all the preparatory work needed to be efficient in the implementation.
- The global semiconductor crisis that has caused long delays and shortages in the supply of semiconductors, which have affected the development of the prototypes in an adequate

time. This added to the difficulties in some cases to buy directly from extra-EU companies.
- A general lower-than-expected readiness and quality of the sensors, that required multiple tests and changes, slowing down the preparation of the final prototype for the environmental installation.
- Legal limits and constrains for the installation of the sensors in the first application proposed (monitoring of the ventilation systems on the buildings' roofs) that didn't allow the application of the sensors in real conditions (although in general the prototype didn't match the expectations).

8.1 Current situation and next steps

The activities are ongoing, and the sensors are currently collecting measurements and data. For this reason we expect that the activity will provide the expected answers in the next 6 months. Although this would be after the end of the project, we think it is important to continue the effort also to avoid a loss of resources, in particular the personnel costs (the sensors are not robust enough to be used in the open environment for long time).

9 Conclusion

It is essential to develop new technologies that can help to expand the monitoring networks in harmony with the concept of a smart city. The possibility to use IoT and low cost sensors would allow the creation of large networks that are critical to monitor the heterogeneity that characterises the urban environments. These technologies would simplify environmental monitoring, making it more sustainable at both the environmental and economic levels, while ensuring low maintenance and installation costs.

The test performed in the project activities highlighted that these sensors although have some potential are still far from the high quality systems. Nevertheless for specific uses they could be the only realistic alternative. For this reason, a number of tests have been started and that are still currently ongoing. With the fast development of technologies and computational tools, in the next years it is expected that IoT systems will be largely used in environmental applications connected to the CO2 monitoring.

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