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Smart Citizen Kit and Station: An open environmental monitoring system for citizen participation and scientific experimentation

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ABSTRACT

In the past years, multiple research projects have explored the potential of low-cost environmental sensors for urban air pollution monitoring. However, each project has taken its own independent and in many cases, fully or partially closed approach. We present the Smart Citizen System, a flexible, easy-to-use and fully open-source environmental monitoring solution for particulate matter, carbon monoxide, nitrogen dioxide, noise levels, and many other indicators. The use of low-cost sensors in recent years has been generally approached in two different ways citizen science and educational activities, where the primary purpose is to engage citizens in the measurement process and raise awareness of environmental concerns; and a more sophisticated scientific approach, where the main aim is to study the potentiality of the low-cost sensing technologies. The Smart Citizen System balances modularity with integration to fulfil both needs by providing an extendable solution, with different ranges of sensors based on the same core components. With that aim, two solutions have been developed: the Smart Citizen Kit, intended for citizen science and awareness activities; and the Smart Citizen Station, designed to serve as a more complex and accurate set of air pollution sensors. The design is based on the principle of reproducibility, also integrating non-hardware components such as a dedicated storage platform and a sensor analysis framework. The core system bases its sensing capabilities in widely reviewed low-cost sensors and aims to provide a robust framework for environmental monitoring activities. By making everything open, from the hardware to the software platform or the sensor post-processing algorithms, we hope others might find it useful as a development platform allowing them to focus on their project particular needs instead of reinventing everything from the ground-up.

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Specifications table:

Hardware name	*Smart Citizen Kit and Smart Citizen Station*
Subject area	• *Educational Tools and Open Source Alternatives to Existing Infrastructure*
Hardware type	• *Field measurements and sensors*
Open source license	*CERN Open Hardware License v1.2 (Hardware Design), GNU GPL v3.0 (Firmware), GNU AGPL v3.0 (Software Platform)*
Cost of hardware	*Smart Citizen Kit~100 eur and Smart Citizen Station~800 eur*
Source file repository	*Multiple, see Annex*

1. Hardware in context

The Smart Citizen System is a complete set of modular hardware components aiming to provide tools for environmental monitoring, ranging from citizen science and educational activities to more advanced scientific research. The system is designed in a extendable way, with a central data logger with network connectivity to which the different components are branched (Fig. 1). The system is based on the principle of reproducibility, also integrating non-hardware components such as a dedicated storage platform [43] and a sensor analysis framework [45].

The core system bases its sensing capabilities in widely reviewed (Rai et al.) [1] low cost sensors, and aims to provide a solid framework for environmental monitoring activities. Each of the modules shown in Fig. 2 is described under the Section 2.

Additionally, the system is meant to serve as a base solution for more complex settings, not only related with air quality monitoring. For that purpose, in addition to the modules that are described further in the following sections of this article, the system also provides off-the-shelf support for a wide variety of third party sensors, using the expansion bus from Fig. 2 as a common port. An example of this support is given in the Section 2 of this article.

1.1. Motivation and purpose

The use of low cost sensors in recent years has been generally approached in two different ways [33]: citizen science and educational activities [12], where the primary purpose is to engage citizens in the measurement process and raise awareness of environmental concerns; and a more sophisticated scientific approach, where the main aim is to study the potentiality of the low-cost sensing technologies. The Smart Citizen System aims to fulfill both needs by providing an extendable solution, with different ranges of sensors based on the same core components. With that aim, two solutions have been developed: the **Smart Citizen Kit**, intended for citizen science and awareness activities; and the **Smart Citizen Station**, designed to serve as a more complex and accurate set of air pollution sensors. The two solutions are described in Sections 2.3 and 2.4 of this article, respectively.

The Smart Citizen System was developed with the aim of creating a fully open and flexible solution, while other marketed options only allow for a limited amount of metrics. For instance, PurpleAir [32] provides a low-cost sensing solution that is only capable of measuring temperature, humidity, pressure and particle matter. A similar sensor to that used by PurpleAir, such as the SDS011 Fine dust sensor, is used by LuftDaten [24], but with the same limitations regarding atmospheric

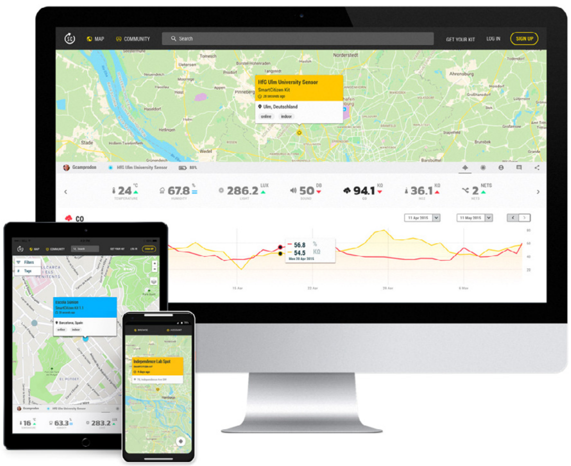

Fig. 1. Smart Citizen Platform.

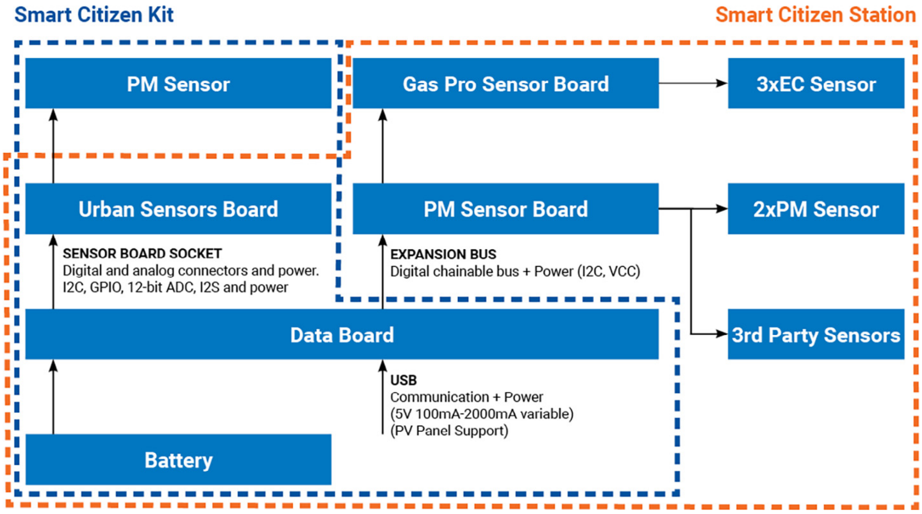

Fig. 2. Smart Citizen System.

chemical composition measurements. On the other hand, EarthSense UK [14] uses a very similar solution to the base solution proposed in this article, with electrochemical sensors and particle matter sensors, while also allowing for additional cartridges in the electrochemical sensors. While both systems use a similar hardware solution, the Smart Citizen System provides a more open approach, allowing end users to be part of not only the measurement activities but also of the analysis and development process. To summarize, the Smart Citizen System aims to:

1. Provide a low-cost sensing solution for citizen science and awareness activities.
2. Provide an open source end-to-end solution for scientific development (sensing, data storage and data post-processing).
3. Provide an all-in-one educational tool that is both low cost and open source.

The current hardware presented in this publication builds on the legacy of previous generations of the Smart Citizen project and has been developed as part of the of iSCAPE (Improving Smart Control of Air Pollution in Europe) project, which is funded by the European Community's H2020 Programme (H2020-SC5-04-2015) under the Grant Agreement No. 689954. In the following sections, this will be referred to as simply "the iScape Project".

2. Hardware description

In this section, the different components which make up the Smart Citizen System are described. Building from these components, both the Smart Citizen Kit and the Smart Citizen Station are described in Sections 2.3 and 2.4.

2.1. Individual Components

The different individual components which make up the Smart Citizen System are detailed in the following paragraphs.

2.2. Data Board

The data board (Fig. 3) is a data-logger at the core of the sensors architecture supporting the Smart Citizen Kit and the Smart Citizen Station. This module is powered by an ARM M0 + 32-bits at 48Mhz running the Smart Citizen Firmware [40], combining the low power consumption of the ARM M0 family with the power of a 32-bits processor with 32 KB of RAM and 256 KB of FLASH memory [26]. This solution offers enough program storage and memory space to support multiple auxiliary sensors. This chip is used by the Arduino Zero and MKR boards, therefore benefiting from the open community built around these boards in particular and the Arduino project [7] in general.

The data board also includes a Wi-Fi module, a micro SD card slot, an internal Flash and a battery management solution. In addition, it includes 4 MB of extra Flash Memory for offline data storage, in case of network brownouts. The Wi-Fi Module is the well-known Espressif ESP8266 [15] IEEE 802.11 b/g/n Wi-Fi with 4 MB Internal Flash for web content storage. Although a more advanced chip possibility, such as the ESP32, would be an improvement over this architecture, the ESP8266 is kept for development reasons, since all previous iterations of the Data Board are based on this solution. Both, the SAMD21 and the ESP8266 controllers are shown in Fig. 4. The micro SD card slot and the internal Flash are shown in Fig. 5:

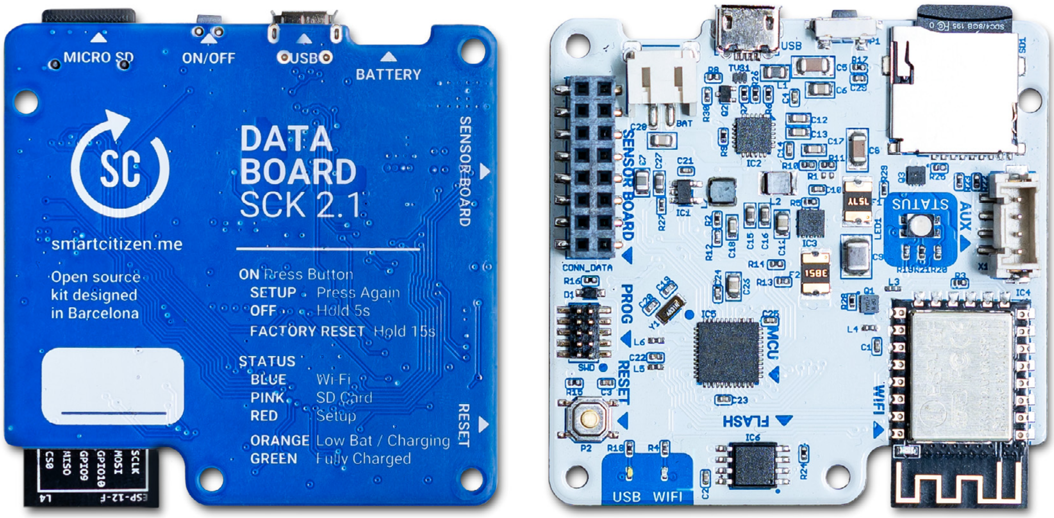

Fig. 3. Data Board.

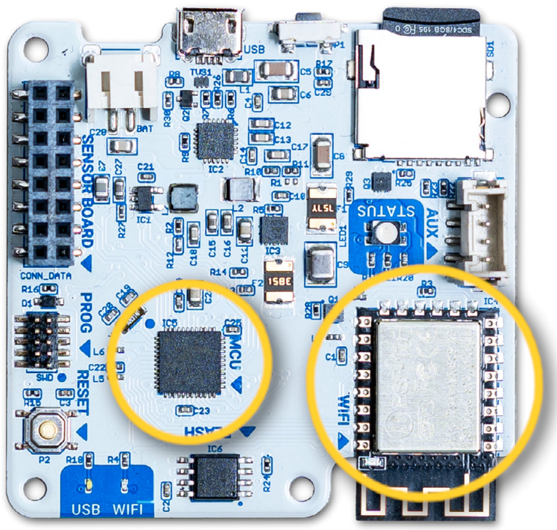

Fig. 4. Data Board – SAMD21 and ESP8266 controllers.

The data board also includes a Seeed Studio [36] standard Grove connector where off-the-shelf modules from the same manufacturer can be connected (Fig. 6). The connector supports an independent I2C bus by default, but by software it can be configured to support other uses (GPIO, I2C and UART). It can supply power up to 750 mA, and it can be enabled or disabled by software to save power.

In addition, a header connector, which exposes a set of pins from the SAMD21 chip, is mounted to the data board (shown in Fig. 6), providing a means of connection to the Urban Sensor Board or any other as described below. The Urban Sensor Board, described in the following paragraph, includes a selection of low-cost sensors aimed at urban environmental monitoring, but this board could be replaced by other hardware using the pinout as described in Table 2. The Smart Citizen Gas Pro Sensor Board and Smart Citizen PM Sensor boards described in the following paragraphs use this bus to receive power and communications from the board. An example of sensors logged via the auxiliary connector is shown in Fig. 7.

The board includes a power unit, with a battery management system, capable of handling a variety of Lithium polymer cells. The batteries are connected to a standard JST-2 pin battery connector. The Smart Citizen Kit described in Section 2.3 by default uses a 2000 mA h battery, but larger capacities can be used. Under normal conditions, and depending on the sensors enabled, a 2000 mA h battery can last between 24 h (with all sensors enabled, and a 1-min recording frequency) to more than a week. The board also features a *sleep mode*, through which drastically lower average consumption are achieved. Further details are given in Table 1.

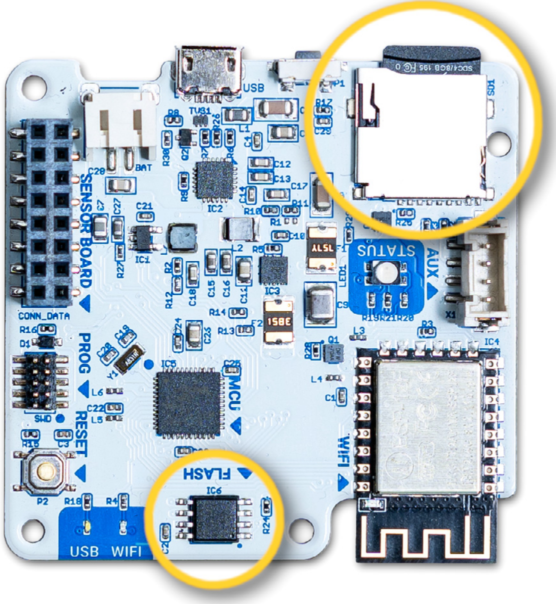

Fig. 5. Data Board – Storage.

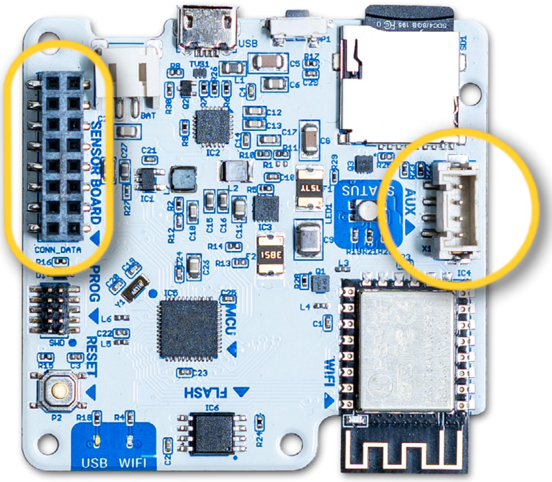

Fig. 6. Data Board Sensor Connectors.

Furthermore, the controller allows the batteries to be easily charged using the board's micro USB connector with any standard USB power adapter outputting 5 V. The normal time for completely charging the stock battery is between 2 and 3 h. Both connectors are shown in Fig. 8. It is also possible to use solar panel (5 V) to charge the SCK.

The data board features a set of user interfaces which provide feedback to the user, as well as two buttons with different functionalities. The main RGB LED provides general feedback of the data board status. A full description of this is shown in Section 5 of this article. Two additional LEDs provide information regarding the WiFi and USB status. All three LEDs are highlighted in Fig. 9:

Additionally, two buttons are provided for user action. A hardware reset button, which forces a power cut to the board, and a power button, used to change the device's mode, turn on and off the device, and to perform a factory reset. These interfaces are shown in Fig. 10:

The data board also features a set of connectors for more advanced users. The micro USB is used for serial interface, allowing the user to program both the SAMD21 and the ESP8266 controllers. A custom CLI has been implemented on the data board firmware to serve commands. These commands are detailed in Section 5 of this article. Finally, an SWD (Serial Wire Debug) is included for the debugging and programming of the SAMD21 microcontroller and is shown in Fig. 11.

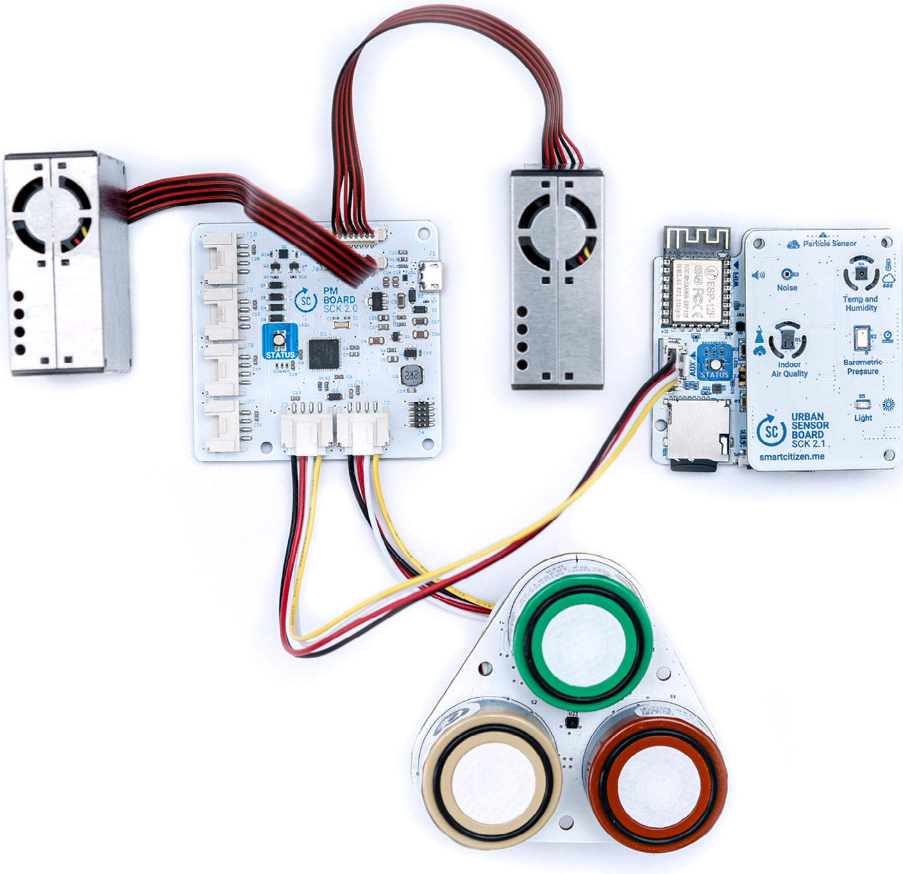

Fig. 7. Data Board – Example of expansion bus usage.

Table 1
Power Consumption.

Component	Current (mA)
SAMD21 in sleep mode	<5
SAMD21 + required auxiliaries	16
ESP8266X	60
PMS5003	~100
Gas Pro Board	25
PM Board (without PMS5003)	35

NB: in the V2.1 of the Data Board, VCC includes both, 5 V and 3.3 V. V2.0 only includes 3.3 V.

Finally, the data board rear face is intentionally designed to be component-free, allowing for easier handling and installation on different surfaces or enclosures.

2.2.1. Urban Sensor Board

The Urban Sensor Board is a solution that contains a selection of low-cost sensors for environmental monitoring [1] (Fig. 12). Its main purpose is to serve as a tool for citizen science and awareness activities, and for that reason, metrics such as temperature, pressure, and humidity, as well as noise levels, ambient light, air quality indicators and PM sensors are included. The Urban Sensor Board has undergone several modifications throughout its development, and its current version is V2.1. The sensors present in the Urban Sensor Board V2.1 are detailed in Table 3. As explained in Section 2.3, the combination of the Data Board and the Urban Sensor Board creates the Smart Citizen Kit.

The Urban Sensor Board connects to the Data Board via header connector as shown in Fig. 13:

Following the same principle as the data board, the front face of the Urban Board is intentionally component free, except for the sensors themselves, allowing for better visibility of each sensor, making it useful for demonstrations in educational environments.

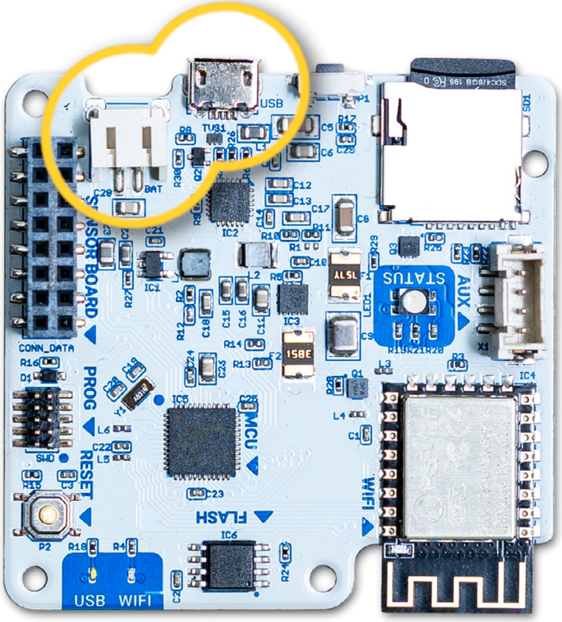

Fig. 8. Data Board Power Connectors.

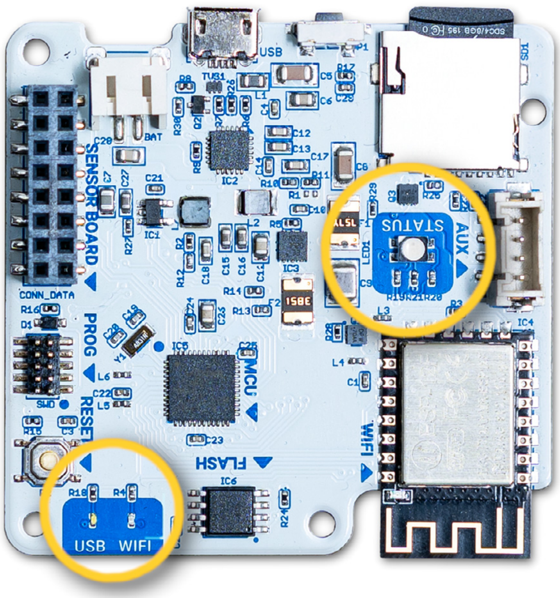

Fig. 9. Data Board User Feedback LEDs.

2.2.2. PM Sensor Board

The PM Sensor Board is an auxiliary board capable of managing a wide variety of connections. It is mainly intended to serve as an I2C bridge between the Data Board and several other types of sensors, as well as to provide an off-the-shelf connection to the Plantower PMS5003 sensors [30] supporting JST-XH [22] connectors. These sensors were selected explicitly due to the sensor benchmarking done by other investigators into low-cost solutions (Rai et al.) [1] and further evaluations by academics in the field (Sayahi et al. [34], Jayaratne et al. [21], and Badura et al. [9]).

The PM Sensor Board runs a dedicated ARM M0 + 32-bits, the same as the Data Board, to provide a unified hardware architecture. The board includes a step up to provide 5 V to drive the PM sensors and a disable/enable circuit to turn off

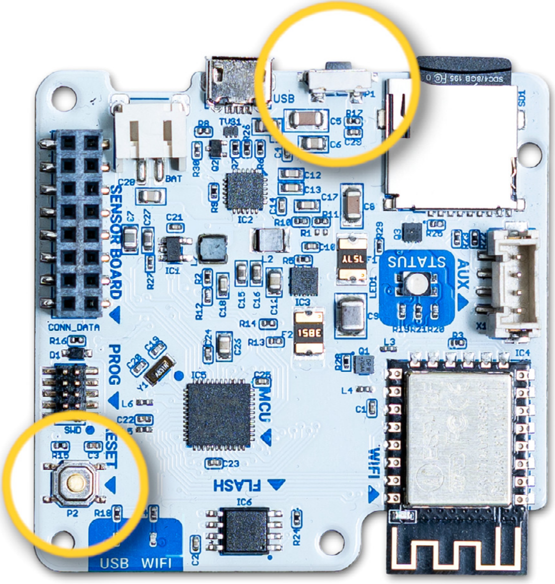

Fig. 10. Data Board Buttons.

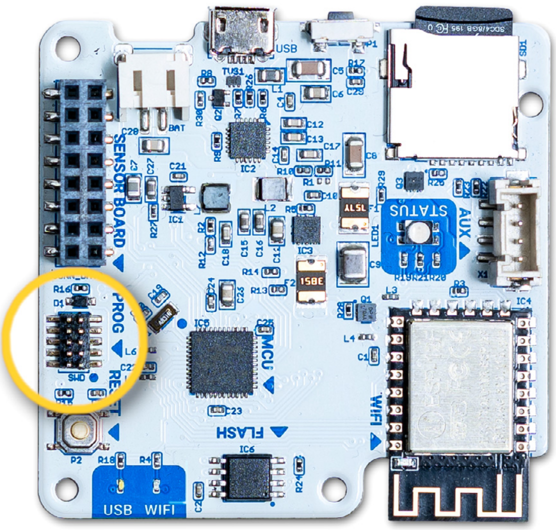

Fig. 11. SWD connector.

Table 2
Data Board Header Connector Pin-out.

SAMD21 Pins	SCK Pins	SCK Connector		SCK Pins	SAMD21 Pins
GND	GND	16	15	GND	GND
GND	GND	14	13	GND	GND
PA11	I2S_FS	12	11	TX	PB2
PA7	I2S_SD	10	9	RX	PB3
PA10	I2S_SCK	8	7	5 V	5 V
PA22	SDA	6	5	PWM_CO	PA9
PA23	SCL	4	3	PWM_NOX	PA8
VCC	VCC	2	1	VCC	VCC

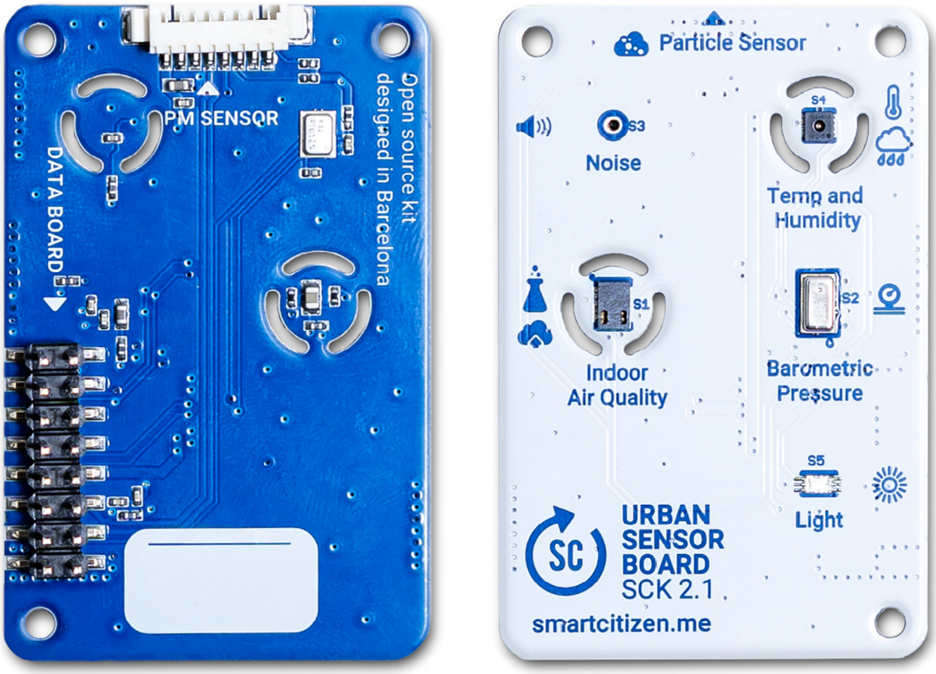

Fig. 12. Urban Board.

Table 3
Urban Sensor Board V2.1.

Measurement	Units	Sensor
Air Temperature	°C	Sensirion SHT-31
Relative Humidity	% rh	Sensirion SHT-31
Noise Level and FFT Spectrum	dBA, dBC, dBZ	Invensense ICS-434342
Ambient Light	Lux	Rohm BH1721FVC
Barometric pressure, AMSL (Metres above sea level)	kPa, m	NXP MPL3115A26
eCO2 and eVOC	ppm	AMS CCS811
Particulate Matter PM2.5 (external)	µg/m^3	PMS 5003

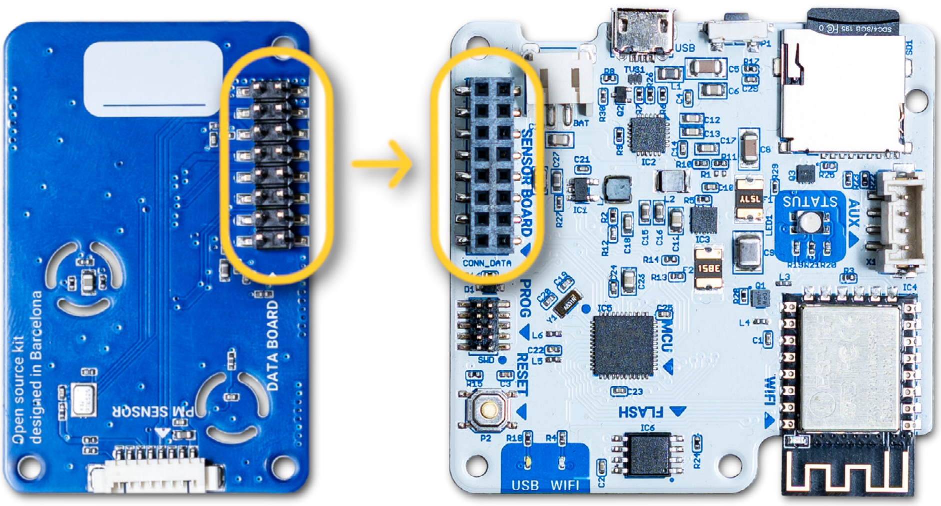

Fig. 13. Urban Sensor Board to Data Board.

the sensors via software. Finally, this board includes a standard set of Grove Connectors, including an I2C bridge, a 12bit ADC, GPIO pins and UART interfaces. An image of the PM Board is shown in Fig. 14.

Additionally, user feedback is provided through an RGB LED, showing the current status of the board. The different statuses of the board are detailed in Table 4.

2.2.3. Gas Pro Sensor Board

The Gas Pro Sensor Board (Fig. 15) is an auxiliary board with high-end potentiostatic circuits driving 3× Alphasense Ltd, shown in Table 5. These electrochemical Series B Gas Sensors [6] are designed for ultra-low noise, high-performance, and low power consumption. This board includes an additional temperature and humidity sensor (Sensirion SHT31), providing a measure of the actual tempertature of the electrochemical sensor. Furthermore, an additional Grove connector is included in the board to serve as an I2C bridge.

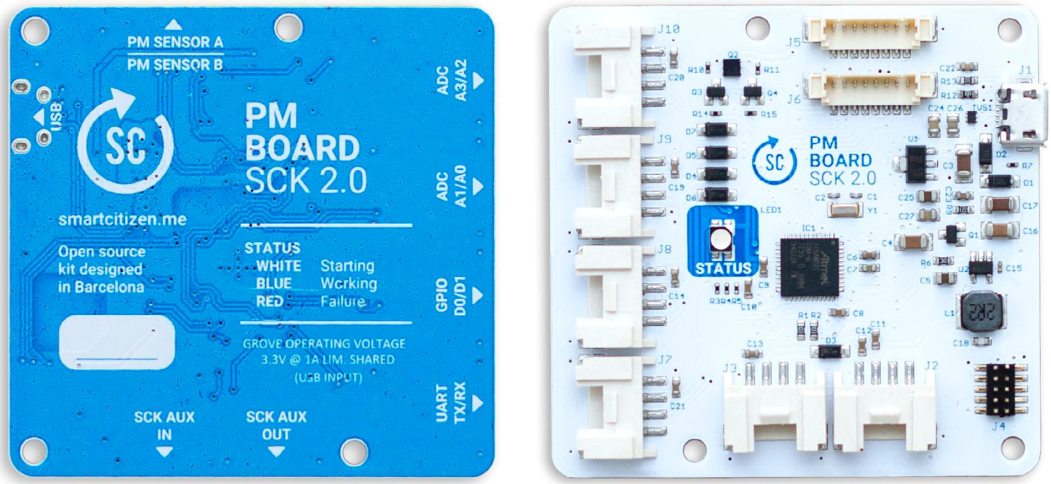

Fig. 14. PM Sensor board.

Table 4
PM Board LED Statuses.

Color	Status
WHITE	Initialising board
BLUE	Normal functioning
RED	Failure

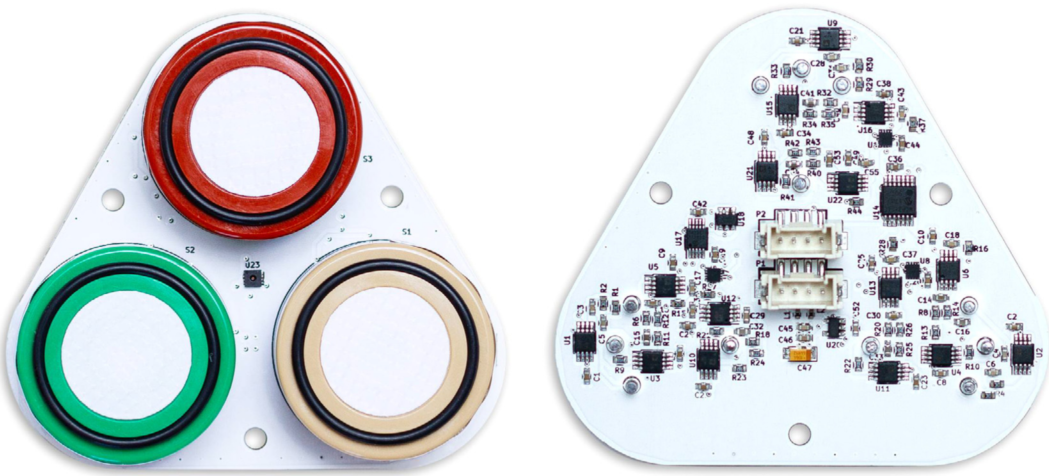

Fig. 15. Gas Pro Board with 3× Alphasense Ltd. Electrochemical sensors.

Table 5
Alphasense Ltd. Sensors used in the Gas Pro Sensor Board.

Measurement	Units	Sensor
Carbon Monoxide	ppm	Alphasense CO-B4 [3]
Nitrogen Dioxide	ppb	Alphasense NO2-B43F [4]
Ozone	ppb	Alphasense OX-B431 [5]
Temperature	°C	Sensirion SHT31
Relative Humidity	% rh	Sensirion SHT31

The selection of the sensors was based on the wide variety of literature available on them. Both Penza and EuNetAir Consortium (2014) [53] and Mead et al. (2013) [25] test the NO2A1-A3 against reference instruments, in the laboratory as well as in the field, with well-correlated results. The former concluded that the Data Quality Objective for "indicative measurements" (European Parliament and Council of the European Union, 2008) [18] is fulfilled, and the latter report sensitivity in the low ppb region with high linearity. Spinelle et al. 2015 [50] tested the Alphasense NO2B4 and O3B4 in a field experiment, with various calibration approaches. Performance evaluation of the same sensors was performed later including a test on a wide range of performance parameters (e.g. response time, calibration function, repeatability, drift, hysteresis effect, and matrix effect) (Spinelle et al. 2017) [51]. The experiment found a strong correlation with reference instruments ($R^2 > 0.9$) and identified some cases with significant hysteresis effect related to humidity. In chamber conditions, the performances of the Alphasense CO-B4 was found to be excellent, with the R^2 values being greater than 0.9 (Castell et al. 2017 [11]; Mead et al. 2013 [25]; Sun et al. 2016) [52]. Two field studies reported moderate to excellent R^2 values (0.53–0.97) for the CO-B4 sensor (Castell et al. 2017 [11]; Mead et al. 2013) [25]. Finally, some calibration approaches as detailed in Popoola et al. (2016) [27] and Hagan et al. (2018) [19] are used in the post-processing stage as a basis for pollution concentration calculations.

Finally, the Gas Pro Sensor Board is tested with a custom Tester Board which sends a finely controlled current source to each of the electrodes (Fig. 16). By monitoring this current, the Gas Pro Sensor Board voltage measurement is validated if each current set-point on the tester board is measured distinctively, with a 0.1 mV error threshold.

2.2.4. Third party sensors

As mentioned above, the expansion bus on the data board is meant to power and communicate with additional sensors beyond those presented in this article. As an example, Fig. 17 shows a soil monitoring solution based on the Atlas Scientific Ezo Family [8] of sensors, with pH, conductivity, and temperature boards as well as probes, and a WeMakeThings Chirp [54] Capacitive Soil Moisture Sensor. This solution is fully controlled via the I2C in the expansion bus on the data board.

2.2.5. Firmware

The Smart Citizen System firmware is comprised of three parts: (1) the primary processing tasks are done by the SAMD21 microcontroller firmware; (2) the tasks related to network communication are run through the ESP8266; and (3) the firmware that runs in the PM Sensor Board, which provides a unified I2C interface for additional sensors. This is shown in Fig. 18.

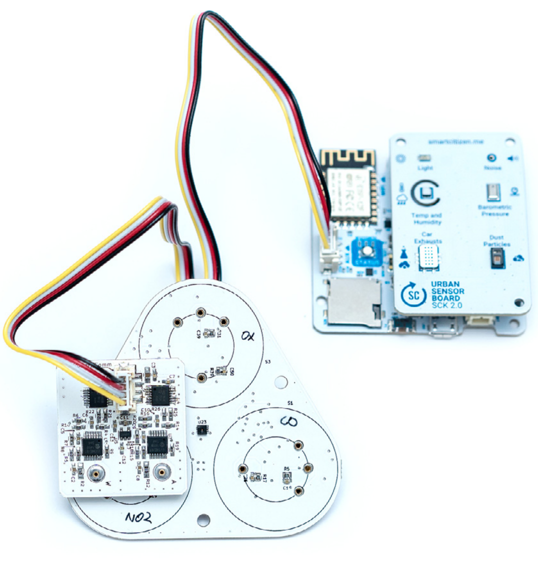

Fig. 16. Gas Pro Board being tested with the Tester Board.

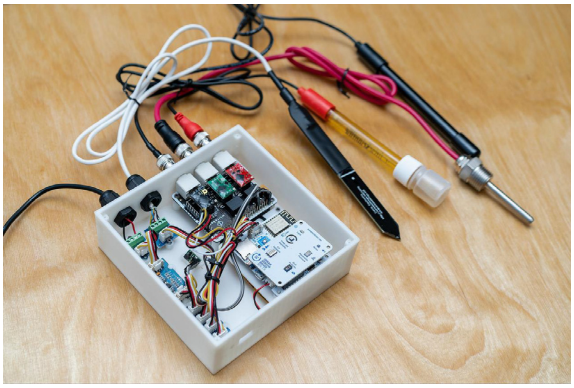

Fig. 17. Third party soil monitoring solution.

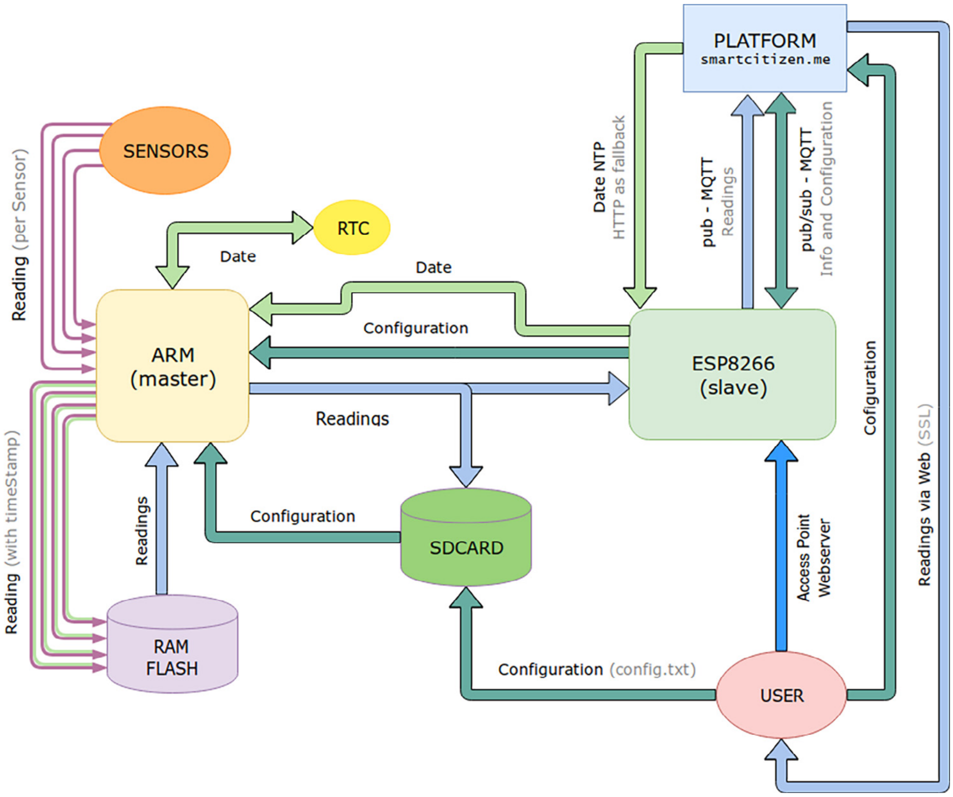

Fig. 18. Firmware architecture.

The **SAMD21 firmware** is divided into different subsystems:

- **Main:** Manages the overall tasks based on the inputs received from the different subsystems, triggers reading and publishing of sensors, communication with the ESP microcontroller, etc.
- **Power:** Manages battery and USB power input detection, battery level updating, and battery charging. This subsystem provides information that defines the feedback provided to the user related to battery and charging status, also sleep and low power measures are taken based on this data.
- **Configuration:** Takes charge of updating configuration on the kit and saving ans restoring configuration values. The configuration can be changed through several channels like: the web interface or the platform (changes arrive via Serial Port from the ESP8266), the USB console system or the sdcard configuration file.

- **User interaction:** Manages user interaction with the kit through the multi-purpose button and gives feedback with the Status LED.
- **Sensor interface:** Abstracted interface to interact with the different sensors that are supported by the stock firmware. It offers methods to detect, start, stop, read, and in some cases control each sensor. Each real sensor can be divided into several virtual sensors to provide a reading of different properties: i.e. battery voltage, battery charge rate, etc. The sensor interface is divided in 3 main groups based on the physical location of the actual sensors:
  - **Base Sensors:** battery and sdcard.
  - **Urban Sensors:** temperature, humidity, light, etc. (the full list can be found on Table 3)
  - **Auxiliary Sensors:** External sensors connected to the auxiliary I2C interface including but not limited to the Gas Pro Board, PM board and supported third party sensors. We encourage integration of all type of external sensor libraries.
- **Console Interface:** Provides a simple way to interact with the Smart Citizen Kit through a serial terminal via the USB port. In the source code we provide a simple way to define and add new commands to extend the possibilities and complexity of the interaction with the kit. This Interface already provides a long list of commands that include for example: Wi-Fi configuration, sensor enabling/disabling control and configuration, reading and real time monitoring of sensors, diagnose and debug tools, etc.

The **ESP8266 firmware** manages network related tasks. It communicates via the UART interface with the SAMD and takes care of tasks like obtaining date and time via NTP protocol, publishing data to the Smart Citizen platform MQTT broker, setting up an access point to allow user setup, and software updates through a web interface. This firmware has been designed so that it is easy to port to other microcontrollers and so that the ESP8266 can be replaced with other types of radio hardware like LoRa modules.

The **PM Sensor Board firmware** presents a unified I2C interface to the Base Board which allows for the simultaneous use of multiple sensors connected to the Base Board through supported interfaces.

2.3. Smart Citizen Kit

The Smart Citizen Kit is made up of the Data Board and the Urban Sensor Board. Additionally, without any further boards, a PMS5003 can be branched to the Urban Sensor Board to measure PM data (Fig. 19).

The measurements that the Smart Citizen Kit can perform are detailed in Table 3. As mentioned above, an additional set of sensors can be plugged into the Auxiliary port, extending the kit's capabilities. This sensing unit is oriented for citizen science and awareness activities, as well as educational purposes.

The enclosure (Figs. 20 and 21) for the Smart Citizen Kit V2.1 implies a significant redesign in order to improve its waterproofness and thermal properties from previous versions. The final design will be included in the Enclosures Repository [39]. This enclosure is intended as a primary 3D printed solution, but can be modified for different configurations and needs.

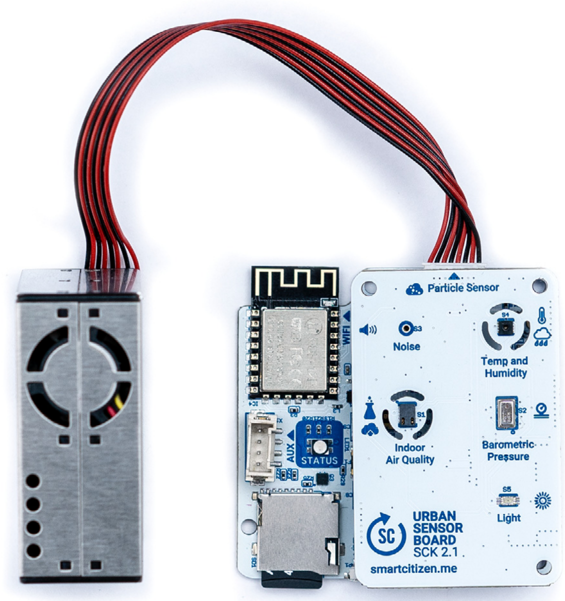

Fig. 19. Smart Citizen Kit V2.1.

Fig. 20. Smart Citizen 3D printed enclosure.

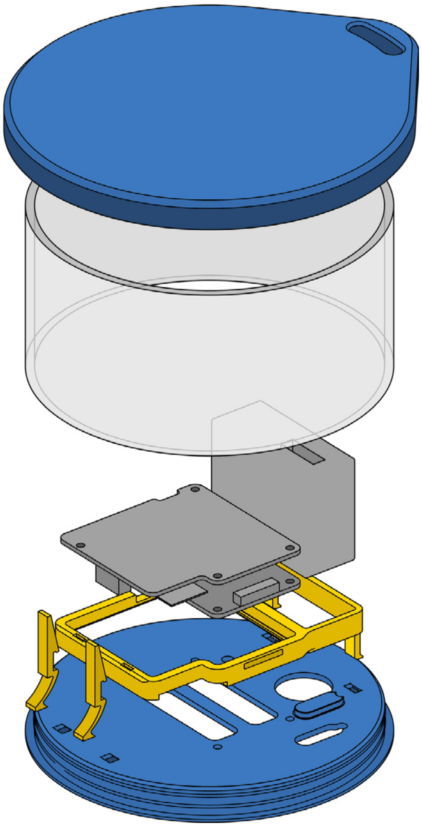

Fig. 21. Smart Citizen V2.1 enclosure. Exploded view.

2.3.1. Physical dimensions

The Smart Citizen Kit dimensions are listed below for reference:

- Dimensions: 60 × 60 × 20 mm (approx.)
- Dimensions w/V1.5 enclosure: 110 × 110 × 50 mm (approx.)
- Dimensions w/V2.1 enclosure: ø 120 × 70 mm (approx.)
- Weight: 65 g
- Weight w/enclosure: 160 g

2.4. Smart Citizen Station

The Smart Citizen Station is comprised of all the components detailed in the Smart Citizen System:

- A Data Board as a central data logger and connection manager
- An Urban Sensor Board for basic environmental metrics, as well as noise pollution and air quality indicators
- A Gas Pro Sensor Board, with 3xAlphasense Series B electrochemical sensors [6] (Table 5)
- 2 × Plantower PMS5003 [30] sensors, working in an alternating fashion for battery savings and data deviation checking
- A PM Board bridging the data board, the Gas Pro Sensor Board and the PMS5003 sensors
- A modular enclosure for outdoor exposure

The unit was designed for outdoor functioning, and the results of its evaluation and further iterations are shown in Section 7 of this article. The materials of the Smart Citizen Station V1.0 are low-density HDPE, easily machinable in a 2.5-axis CNC and laser cut acrylic cover. The main principle for this design is to allow for its easy fabrication within a Fablab [16]. In Table 6, a complete list of the sensors included in the Smart Citizen Station is detailed.

The enclosure for the Smart Citizen Station has undergone several revisions throughout its development. An initial iteration was developed using off-the-shelf components, as shown in Fig. 22.

The Smart Citizen Station V1.0 is shown in Fig. 23. This version is currently being evaluated and some of the results of this evaluation are detailed in Section 7 of this article. An exploded view of this version is also shown in Fig. 24.

Finally, in order to improve waterproofness, ease of use, and material costs, a third iteration has been developed, and it is shown in Figs. 25 and 26. In this iteration, an additional thermally-formed cover has been included, in order to protect the sensors from rain and sun radiation. The power supply has been redesigned and set in an external IP65 box, for ease of installation.

Table 6
Smart Citizen Station full sensor list.

Measurement	Units	Sensor	Component
Air Temperature	°C	Sensirion SHT-31	Urban Sensor Board
Relative Humidity	% rel	Sensirion SHT-31	Urban Sensor Board
Noise Level and FFT Spectrum	dBA, dBC, dBZ	Invensense ICS-434342	Urban Sensor Board
Ambient Light	Lux	Rohm BH1721FVC	Urban Sensor Board
Barometric pressure and AMSL	Pa and Meters	NXP MPL3115A26	Urban Sensor Board
eCO2 and eVOCs	ppm	AMS CCS811	Urban Sensor Board
Carbon Monoxide	ppm	Alphasense CO-B4	Gas Sensor Pro Board
Nitrogen Dioxide	ppb	Alphasense NO2-B43F	Gas Sensor Pro Board
Ozone	ppb	Alphasense OX-B431	Gas Sensor Pro Board
Gases Board Temperature	°C	Sensirion SHT-31	Gas Sensor Pro Board
Gases Board Rel. Humidity	% rel	Sensirion SHT-31	Gas Sensor Pro Board
PM 1	$\mu g/m^3$	Plantower PMS5003	PM Sensors Board
PM 2.5	$\mu g/m^3$	Plantower PMS5003	PM Sensors Board
PM 10	$\mu g/m^3$	Plantower PMS5003	PM Sensors Board
PN size distribution (0.3, 0.5, 1, 2.5, 5 and 10 bins)	#/0.1 l	Plantower PMS5003	PM Sensors Board
Air temperature	°C	Maxim DS18B20	PM Sensors Board

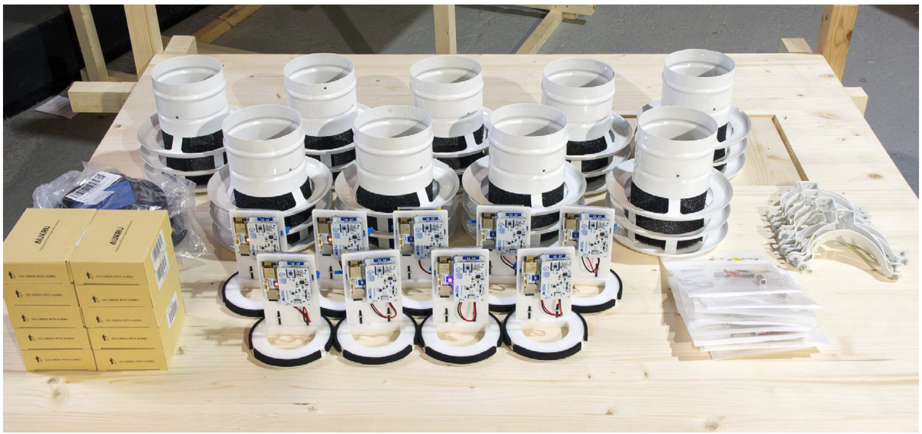

Fig. 22. Smart Citizen Station. First iteration.

Fig. 23. Smart Citizen Station V1.0.

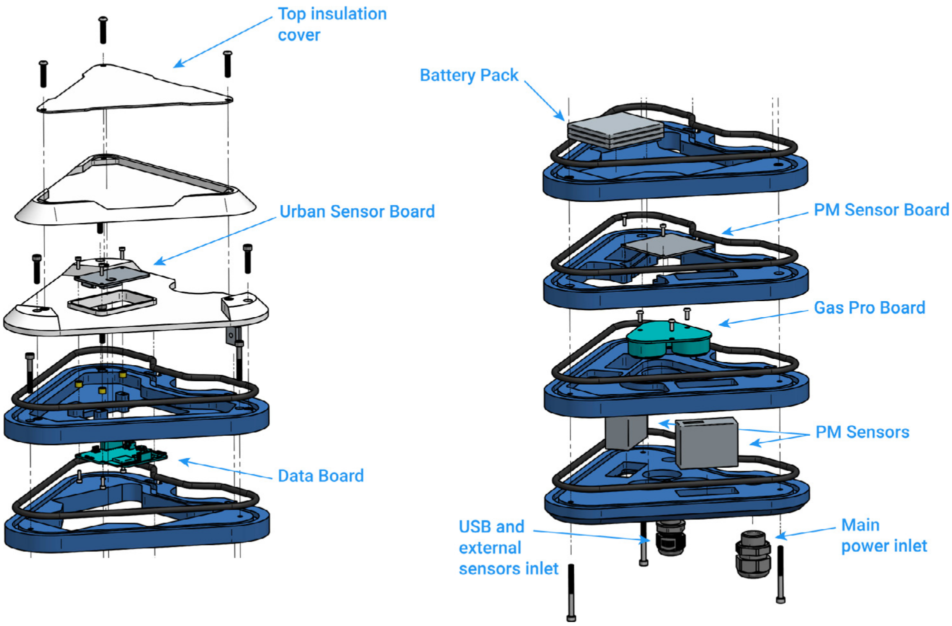

Fig. 24. Smart Citizen Station V1.0: Exploded view.

Fig. 25. Smart Citizen Station V2.0.

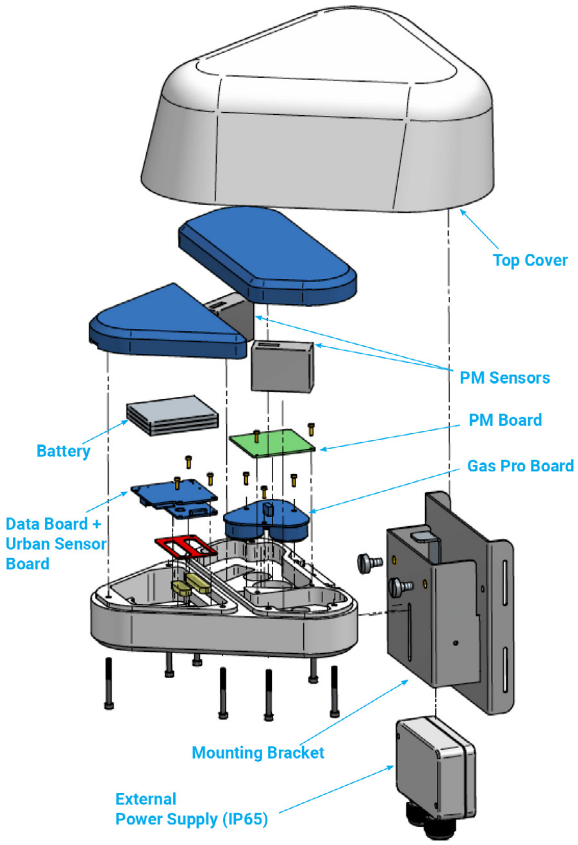

Fig. 26. Smart Citizen Station V2.0: Exploded view.

3. Design files

See Table 7.

Table 7
Design Files Summary.

Description	Design file name/folder	File type	Open source license	Location of the file
Smart Citizen Data Board PCB Design Files	hardware/	Eagle PCB Schematic and Board Layout	CERN Open Hardware License v1.2	https://doi.org/10.17632/pcbz53x967.1
Smart Citizen Data Board main firmware	sam/	Arduino Compatible Firmware (C++/ Platformio)	GNU GPL v3.0	https://doi.org/10.17632/pcbz53x967.1
Smart Citizen Data Board Wi-Fi module firmware	esp/	Arduino Compatible Firmware (C++/ Platformio)	GNU GPL v3.0	https://doi.org/10.17632/pcbz53x967.1
Smart Citizen Urban Sensor Board PCB Design Files	hardware/	Eagle PCB Schematic and Board Layout	CERN Open Hardware License v1.2	https://doi.org/10.17632/pcbz53x967.1
Smart Citizen PM Board PCB Design Files	hardware/	Eagle PCB Schematic and Board Layout	CERN Open Hardware License v1.2	https://doi.org/10.17632/ztw2z2p28h.2
Smart Citizen PM Board firmware	firmware/	Arduino Compatible Firmware (C++/ Platformio)	GNU GPL v3.0	https://doi.org/10.17632/ztw2z2p28h.2
Smart Citizen Gases Pro Board PCB Design Files	hardware/	Eagle PCB Schematic and Board Layout	CERN Open Hardware License v1.2	https://doi.org/10.17632/ynk7dwv6fh.2
Smart Citizen Gases Pro Board Test Util PCB Design Files	hardware/	Eagle PCB Schematic and Board Layout	CERN Open Hardware License v1.3	https://doi.org/10.17632/ynk7dwv6fh.2
Smart Citizen Gases Pro firmware	./	Arduino Compatible Firmware (C++/ Platformio)	GNU GPL v3.0	https://doi.org/10.17632/ynk7dwv6fh.2
Smart Citizen Kit Enclosure	SmartCitizen DIY Clips V2.0–2.1/	STL File	BY-NC-SA	https://doi.org/10.17632/r9bfyxdfw4.1
Smart Citizen Station Assembly Model	SmartCitizen Station V2.0/	STEP File	BY-NC-SA	https://doi.org/10.17632/r9bfyxdfw4.1
Smart Citizen Station BOM	SmartCitizen Station V2.0/	CSV File	BY-NC-SA	https://doi.org/10.17632/r9bfyxdfw4.1

4. Bill of Materials

See Table 8.

4.1. Smart Citizen Station

See Table 9.
Enclosure components are not yet detailed.

4.2. Smart Citizen Kit

Enclosure components are not yet detailed.

5. Build Instructions

The hardware presented in this article is licensed via CERN Open Hardware License v1.2. In the following paragraphs, instructions on how to reproduce the different components are detailed.

5.0.1. Electronic components

The Data Board and the Urban Sensor Board are manufactured and available through the SEEED Studio store [36]. The PM Sensor Board and Gas Pro Sensor Board files detailed in Section 2 of this article are fully available in the hardware repository [37] 464441. These components can be manufactured in a PCB manufacturing service such as SEEED Studio Fusion [35]. At the time of writing this article, we are under negotiations with the SEEED Studio Store in order to make these additional boards available through their store as well.

5.0.2. Smart Citizen Kit Enclosure

The enclosure, as mentioned in Section 2 of this article, is currently being redeveloped for the Smart Citizen Kit. In previous versions, a 3D printed enclosure with a laser cut acrylic was used. All the files are available to download in the enclosures repository [39].

5.0.3. Firmware

The Smart Citizen Kit needs three different firmware components: the SAMD21 bootloader, the SAMD21 firmware, and the ESP8266 firmware. All three are provided via the git repositories mentioned in Section A. To build the Smart Citizen Kit

Table 8
BOM Smart Citizen Station.

Component	Number	Cost per unit (eur)	Total cost (eur)	Source of Material
Smart Citizen Data Board 2.0	1	30.00 eur	30.00 eur	SEEED Studio
Smart Citizen Urban Sensor Board 2.0	1	40.00 eur	40.00 eur	SEEED Studio
Smart Citizen PM Board 2.0	1	22.99 eur	22.99 eur	SEEED Studio
Smart Citizen Gas Sensor Board 2.0	1	129.00 eur	129.00 eur	SEEED Studio
Seeed Studio Universal 4 Pin Buckled 5 cm cable	1	0.32 eur	0.32 eur	SEEED Studio
Seeed Studio Universal 4 Pin Buckled 20 cm cable	1	0.49 eur	0.49 eur	SEEED Studio
Plantower PMS5003 (with cable)	2	12.17 eur	24.34 eur	Plantower
Alphasense CO-B4	1	53.00 eur	53.00 eur	Alphasese LTD
Alphasense NO2-B43F	1	53.00 eur	53.00 eur	Alphasese LTD
Alphasense OX-B431	1	58.00 eur	58.00 eur	Alphasese LTD
6000 mA h LiPo Battery	1	19.90 eur	19.90 eur	Bricogeek

Table 9
BOM Smart Citizen Kit.

Component	Number	Cost per unit (eur)	Total cost (eur)	Source of Material
Smart Citizen Data Board 2.0	1	30.00 eur	30.00 eur	SEEED Studio
Smart Citizen Urban Sensor Board 2.0	1	40.00 eur	40.00 eur	SEEED Studio
Plantower PMS5003 (with cable)	1	12.17 eur	12.17 eur	Plantower
6000 mA h LiPo Battery	1	10.50 eur	10.50 eur	Bricogeek

firmware, *platformio*[31] needs to be installed (the console version is enough, and the full IDE installation is not needed). For the bootloader upload, OpenOCD [28] is also needed somewhere in the user PATH. It is possible to use platformIO provided binary; which is normally located in `~/.platformio/packages/tool-openocd`.

5.0.4. SAMD21 bootloader

The bootloader provided allows the SAMD21 microcontroller to present itself as a Massive Storage Device to the host computer, allowing the user to copy the firmware file to an external drive without the need of installing any software or drivers.

The process of flashing the bootloader requires an SWD compatible programmer (a Raspberry Pi with a proper connector can also be used). The programmer should be connected to the 10 pin SWD connector (shown in Fig. 11) and and to the host computer. Powering the board via USB is also necessary. Once everything is connected, the provided script (`build.py`) will build and upload the bootloader. After finishing this process, the status LED should *breath* in green and the console output should state *Verified OK*.

5.0.5. SAMD21 Firmware

The firmware can be compiled if necessary, and the same build script can be used for all operations. The distributed binaries can also be used without any building process.

To start the firmware upload procedure, double-click on the reset button (shown in Fig. 27). Right after doing so, the kit will show a Mass Storage Device interface to the host computer, and a new drive will appear where the firmware file in *UF2* format can be copied. After a successful flash process, the kit will enter automatically into setup mode (red LED).

5.0.6. ESP8266 firmware

If this is the first upload of the ESP8266 firmware, it must be done through the USB port. Since the ESP8266 chip is not connected directly to the USB interface, the data must be uploaded through the SAMD21 chip. The provided script searches for a Smart Citizen Kit on the USB bus, sending a command to the kit, and enabling the SAMD21 microcontroller to acts like a *serial bridge* (white LED) in order to finally upload the new firmware.

After the first time that this firmware is uploaded, if a firmware upgrade is needed, it can be done via Wi-Fi network upload. Clicking the button of the kit to enter *Setup Mode* (red LED) a Wi-Fi network called *Smartcitizen[....]* will be created. Any connection to this network will be redirected to a web interface that will allow the upload of the new firmware.

5.0.7. Gases Pro Board

The **Gases Pro Board** does not require any firmware installation, and it will expose the necessary I2C devices on the connected bus, so the Data Board can access them directly.

5.0.8. PM Board

The PM sensor board has a firmware that provides support to different sensors and presents them in a unified way, through the I2C interface, to the Smart Citizen Kit.

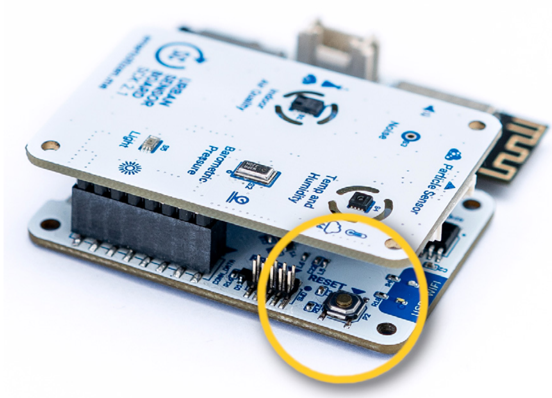

Fig. 27. Reset button.

For building and/or flashing the PM Board firmware, the only requirement is emphplatformio [31]. Once the code is cloned from the git repository and the board is connected through the USB, running the command `platformio run -t upload` inside the *firmware* folder will build and upload the code.

5.0.9. Smart Citizen Station Enclosure

A full display of the Smart Citizen Station V1.0 components is shown in Fig. 28. As mentioned in Section 2, the enclosure of the Smart Citizen Station is built out of low-density HDPE, with additional components including threads, joints, and cable glands. A full BOM is detailed above in Section 4 of this article.

6. Operation instructions

6.1. Common instructions

6.1.1. Setup

The setup of both the Smart Citizen Kit and the Smart Citizen Station begins with the same step of setting up the logging configuration. The process can be followed through a visual and interactive guide as part of the so-called on-boarding application [42]. This application contains instructions on how to assemble and set up the device for data collection [10]. An image depicting several steps of the on-boarding procedure is shown in Fig. 29.

The device can be configured to log data either onto the micro SD card, or to be uploaded via a Wi-Fi network to the Smart Citizen Platform [43]. This process reads as follows:

1. Setting the device to Setup Mode by pressing the power button. The status LED should turn red.
2. Connecting to a temporary WiFi network named SmartCitizen[….] offered by the ESP8266 in Access Point mode. After connecting to this network, the user is redirected to a web interface (Fig. 30).
3. In this interface, the user is prompted to either configure the Kit for SD card logging or to set up Wi-Fi access credentials and input a unique token provided to the user by the on-boarding application.

The device, once configured, will start logging data via the selected mode. The RGB LED provides user feedback, as shown in Table 10.

6.1.2. SD Card Data Retrieval

In order to retrieve logged data from the SD card, the Smart Citizen Kit needs to be turned off by pressing the button for **5 s**, and removing the micro SD card. The micro SD card can be read with a generic SD card adapter. The SD Card contains the following CSV and text files:

- CSV data with timestamp data for all the active sensors
- Text file with internal hardware information, unique hardware identifiers and firmware versions

Finally, the collected CSV data can be uploaded to the Smart Citizen Platform [43] via the user's profile in the Smart Citizen Website [47], under the UPLOAD CSV section.

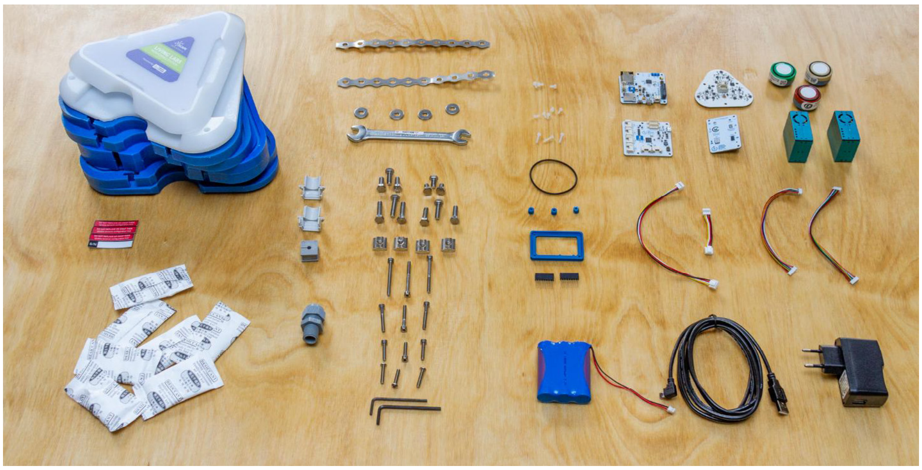

Fig. 28. Smart Citizen Station V1.0 components display.

Fig. 29. On-boarding procedure.

6.1.3. Advanced configuration

As mentioned in Section 2, the Smart Citizen Kit offers a serial console interface via USB cable. Through this interface, users can configure advanced settings related to the various hardware components, the `help` command describes them:

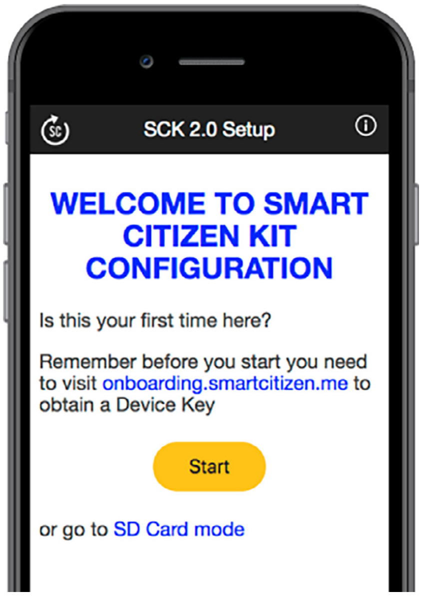

Fig. 30. Smart Citizen Setup mode.

Table 10
User Feedback via RGB LED.

Color	Mode
RED	Setup mode
BLUE	Network mode
PINK	SD Card mode
Fixed WHITE	Device Busy
Fixed GREEN	Firmware Update
Fast ORANGE blink	Charge needed
LED Flashing Frequency	Status
Smooth breathing	OK
Fast blinking	Error
During charging	Status
Single ORANGE blink	Battery charging
Single GREEN blink	Battery full

```
reset:     Resets the SCK
version:   Shows versions and Hardware ID
rcause:    Show last reset cause (debug)
outlevel:  Shows/sets outlevel [ts-bibts-bibts-bibts-bib0:silent, 1:normal, 2:verbosete-bibte-b
           ibte-bibte-bib]
help:      Duhhhh!!
pinmux:    Shows SAMD pin mapping status
sensor:    Shows/sets enabled/disabled sensor [ts-bibts-bibts-bibts-bib-enable or -disable
           sensor-namete-bibte-bibte-bibte-bib] or [ts-bibts-bibts-bibts-bib-interval sensor-
           name interval(seconds) te-bibte-bibte-bibte-bib]
read:      Reads sensor [ts-bibts-bibts-bibts-bibsensorNamete-bibte-bibte-bibte-bib]
control:   Control sensor [ts-bibts-bibts-bibts-bibsensorNamete-bibte-bibte-bibte-bib] [ts-bi
           bts-bibts-bibts-bibcommandte-bibte-bibte-bibte-bib]
monitor:   Continuously read sensor [ts-bibts-bibts-bibts-bib-sdte-bibte-bibte-bibte-bib] [ts-
           bibts-bibts-bibts-bib-notimete-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-n
           omste-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bibsensorName[ts-bibts-bibts-b
           ibts-bib,sensorNameNte-bibte-bibte-bibte-bib]te-bibte-bibte-bibte-bib]
```

publish:	Publish sensor readings
free:	Shows the amount of free RAM memory
batt:	Shows/set the battery state [ts-bibts-bibts-bibts-bib-cap mAhte-bibte-bibte-bibte-bib]
i2c:	Search the I2C bus for devices
charger:	Controls or shows charger configuration [ts-bibts-bibts-bibts-bib-otg on/offte-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-charge on/offte-bibte-bibte-bibte-bib]
config:	Shows/sets configuration [ts-bibts-bibts-bibts-bib-defaultste-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-mode sdcard/networkte-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-pubint secondste-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-readint secondste-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-wifi ‘‘ssid" [ts-bibts-bibts-bibts-bib‘‘pass"te-bibte-bibte-bibte-bib]te-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-token tokente-bibte-bibte-bibte-bib]
esp:	Controls or shows info from ESP [ts-bibts-bibts-bibts-bib-on -off -sleep -wake -reboot -flashte-bibte-bibte-bibte-bib]
netinfo:	Shows network information
time:	Shows/sets time [ts-bibts-bibts-bibts-bibepoch timete-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-syncte-bibte-bibte-bibte-bib]
state:	Shows state flags
hello:	Sends MQTT hello to platform
debug:	Toggle debug messages [ts-bibts-bibts-bibts-bib-sdcardte-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-espcomte-bibte-bibte-bibte-bib]
shell:	Shows or sets shell mode [ts-bibts-bibts-bibts-bib-onte-bibte-bibte-bibte-bib] [ts-bibts-bibts-bibts-bib-offte-bibte-bibte-bibte-bib]
mqtt:	Publish custom mqtt message (’topic’ ’message’)
ram:	View ram stored readings

Each sensor’s reading interval can be changed independently. It is possible to enable or disable every sensor individually, change the publish interval, monitor sensors in real time, among others. Also, there are many functions that can be used to debug and diagnose the different parts of the system.

6.2. Smart Citizen Station

6.2.1. Electronics operation

In the case of the **Smart Citizen Station V1.0**, the Data Board must be accessed in order to manipulate the Data or Urban Boards. To do so, users must remove the first two white HDPE layers by unscrewing the bolts with the necessary hex keys, as shown in Fig. 31. The power supply and the sensors can be accessed in the middle layers and bottom layers respectively.

This operation has been improved on the **Smart Citizen Station V2.0**. In this iteration, the Data Board and the sensors are separated in different areas, and these can be easily accessed by unscrewing the bolts in the bottom of the device. Each area is separated as shown in Fig. 32, being the power supply in an external box.

Fig. 31. Smart Citizen Station V1.0: Access to the electronics.

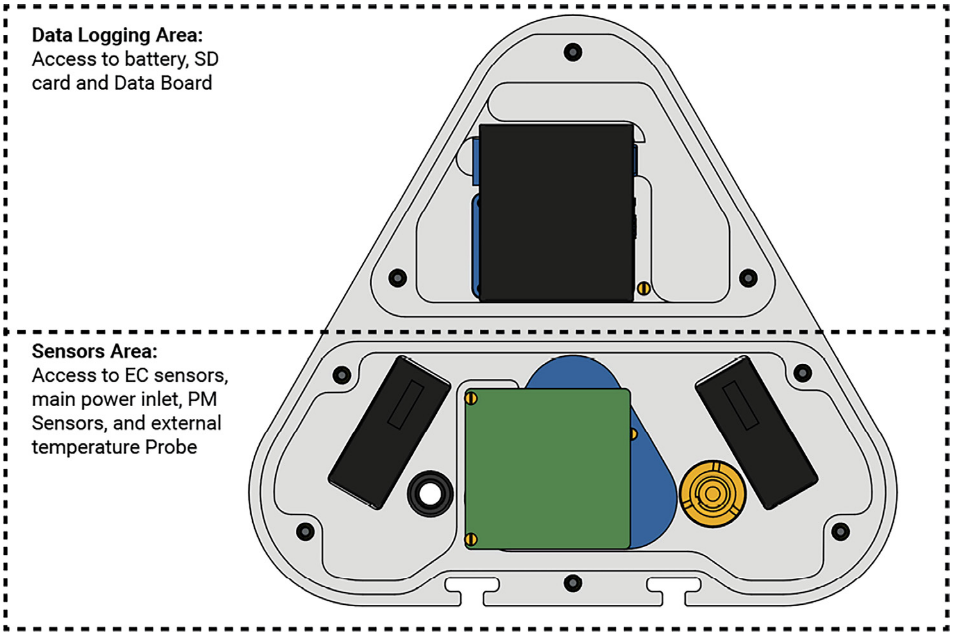

Fig. 32. Smart Citizen Station V2.0: Access to the electronics.

6.2.2. Outdoor installation

A perforated steel strip and M6 threads can be used to mount the Smart Citizen Station on a pole, as seen in Fig. 33. Power can be supplied to the Station V1.0 via USB or normal 230 V plug connection. Internal connections have to be modified for doing so, and detailed graphic instructions are given in the Smart Citizen Documentation [38], and are not detailed in this article for brevity.

In the Smart Citizen Station V2.0, a bracket mounting is provided, as seen in Fig. 26. This bracket holds the body of the station, the cover, and the power supply. The power supply is fitted as shown in Fig. 26. The body of the station can be secured. Finally, since the power supply is in an external IP box, the connection modifications in the Station V1.0 are no longer required to change power supplies.

6.2.3. Sensor considerations

6.2.3.1. Electrochemical Sensors. The electrochemical sensors need stabilization time under the testing conditions they will be at (Popoola et al. [27] and Alphasense AAN106 [2]). It is essential to setup and power the sensors in the test environment with sufficient time before beginning the testing process (between 1 and 2 days for new sensors) [27]. Humidity and temperature extremes will require further sensor adaptation, in order to dry out or absorb the necessary humidity for accurate readings [2].

Finally, the electrochemical sensor capsules should not be removed from the Gas Pro Sensor Board while powered, since this could irreversibly damage the sensor [2].

Fig. 33. Smart Citizen Station V1.0 outdoor installation.

6.2.3.2. Particle Sensor. Environments with large dust concentrations could provoke the accumulation of dust on the sensing elements. Operating under such conditions requires periodic sensor cleaning for representative values.

7. Validation and characterization

In this section, we present details of the hardware validation and characterization process. In order to properly detail the different areas of the hardware presented in this paper, this section is divided into several subsections. Each subsection attempts to cover a range of aspects regarding the system functioning, as well as its limitations and capabilities. The subsections will include:

- Overall functioning and data logging
- Noise data validation
- Ambient data validation
- Air pollution data validation

7.1. Overall functioning and data logging

The Data Board presented in Section 2.2 is capable of logging sensor data to an SD card, as well as sending this data to a dedicated API [43], as presented in Section 1. This data is accessible through dedicated endpoints in the API for each device and can be examined by the users, downloaded as a CSV file, or visualized via in the Smart Citizen Website [47]. This functionality is validated by the data being logged though the API on a consistent basis. This data can be accessed through both the devices endpoint in the API or through the Smart Citizen Website.

Additionally, users without internet connectivity can log their data onto the sensor's SD card in CSV format. This data can later be uploaded through the Smart Citizen Website, via the user's profile section. In the case of a loss of connectivity, the Data Board uses a RAM chip which can store data for later publication, in a LIFO (Last In, First Out) scheme. With regards to network connectivity, the Data Board is able to post data through common network configurations such as Wi-Fi WEP or WPA/WPA2 Personal, but does not support WPA/WPA2 Enterprise with captive portals.

Finally, both the Smart Citizen Kit and Station have been deployed under several different environmental conditions, which have served as iterations to both improve sensor exposure and minimise the risk of malfunctioning due to hardware problems with high humidity levels. Despite these considerations, users should use a rainproof enclosure (as detailed in Section 2).

7.2. Noise data validation

The I2S microphone present in the Smart Citizen Urban Board 2.1 (described in Section 2.2.1) is a digital MEMs microphone from TDK (formerly Invensense), model ICS43432. The internal processing of the noise samples is done using an FFT algorithm, which calculates the weighted spectrum in selectable weighting tables (Z, A or C). This processing is completed with a RMS (Root Mean Square) calculation to obtain the weighted sound pressure level (SPL) expressed in dBZ, dBA or dBC, depending on the weighting table used.

The microphone has been validated in an anechoic chamber, in order to assess its performance and calibrate its frequency response. The tests were conducted in the Laboratory of Acoustics at the University of La Salle, Barcelona, during the month of July 2017. During these tests, a double point comparison between the reference microphone and the ICS43432 was carried out and its results are shown in Fig. 34. For reference, the upper and lower tolerances are extracted from the IEC 61672-1 Standard [20], although there is no particular aim to achieve these targets. In addition, a white noise characterization was performed to assess the frequency spectrum of the Invensense microphone that is mounted on the Smart Citizen Kit. This frequency spectrum is shown in Fig. 35 and is used inversely to equalize the frequency response. The area between 5000 and 7000 Hz is not considered for the equalization, as it is not shown in the ICS43432 datasheet, and it is considered an experimental error or a particular resonance of the PCB:

This microphone can be used, as is, to analyze average noise levels, or analyze the noise spectrum derived from the FFT algorithm. However, the following limitations have to be taken into account:

- The microphone is not omnidirectional, due to its position within the Urban Board.
- The enclosure should prevent resonances in order to avoid measurement errors. A noise-sampling dedicated enclosure has not been developed at the moment of writing this paper, therefore, in situations requiring higher accuracy, it is recommended that the device be used without an enclosure, and with the Urban Board facing the noise source to be analyzed.
- Noise levels below 29 dB and above 116 dB are out of range for the microphone.

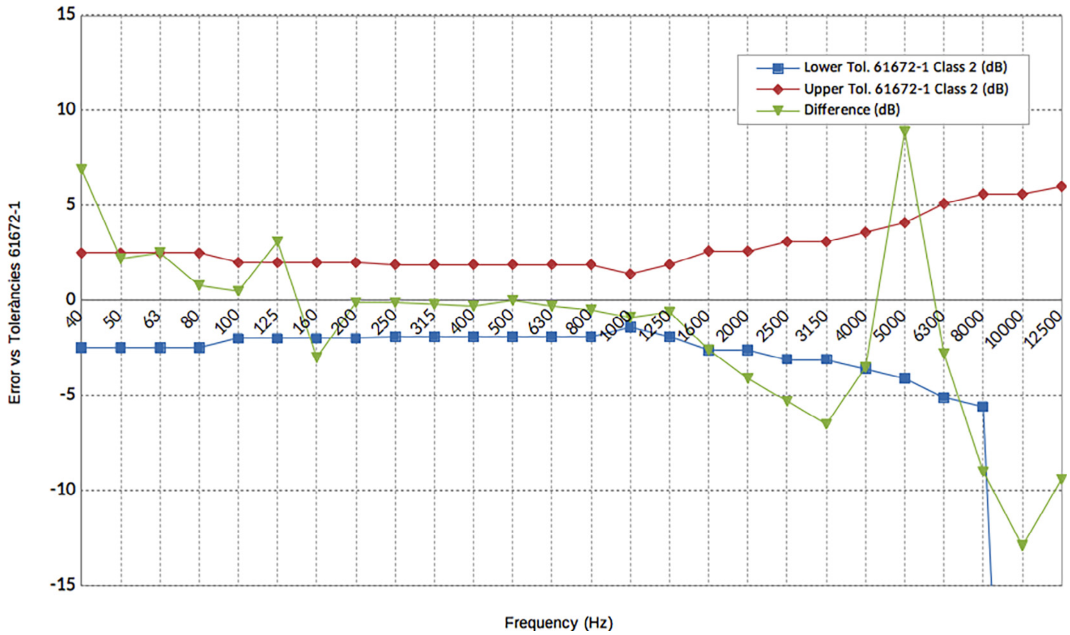

Fig. 34. Raw double point comparison.

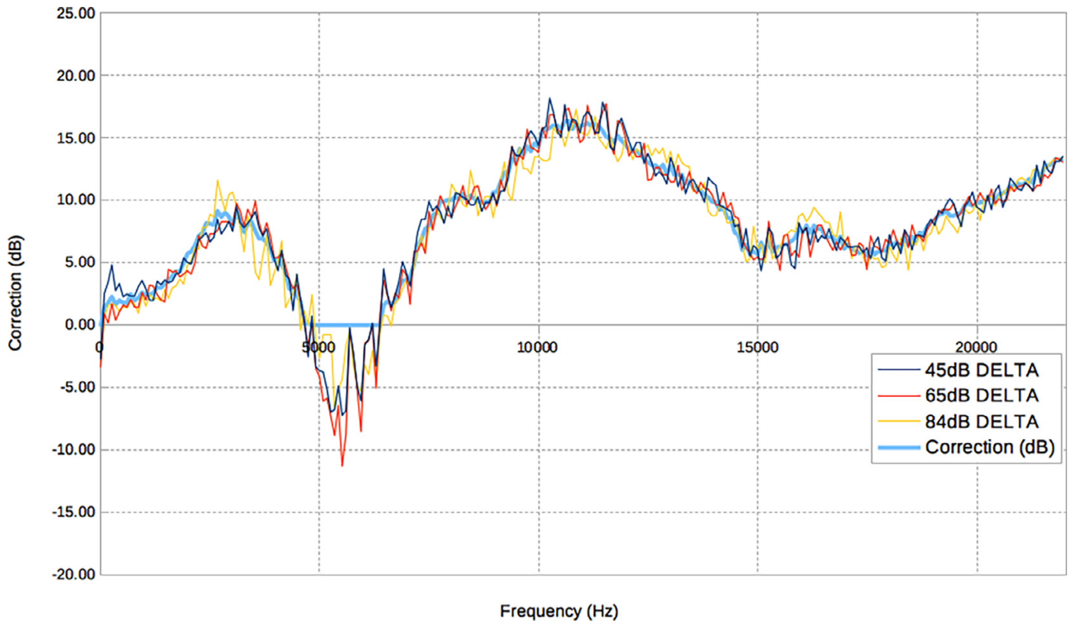

Fig. 35. Spectrum comparison.

7.3. Ambient Data validation

In this subsection, the data from the temperature and humidity sensors are validated. Data from the pressure sensor is not compared with reference measurements, and it is assumed to be correct with the default manufacturer's calibration.

7.3.1. Smart Citizen Kit

In the case of the Smart Citizen Kit, the temperature and humidity measurements are affected by the normal operation of the device, as many of the sensors and components are embedded directly into either the Urban Board or Data Board. The different modes of the device affect the heat emitted from it in different ways. Furthermore, the enclosure and installation conditions (direct exposure to sunlight, for instance), induce undesired temperature and humidity variations that cannot be known beforehand. For reference, in Table 11, the effects from the different modes of operation are detailed, mainly divided into two groups: battery operation vs USB, and sd-card logging vs network:

To account for this, temperature and humidity are corrected by a sequence that triggers periodically and aims to determine the temperature and humidity offset in the installation and operation conditions of the device. As well, the device's charging sequence affects the heat released, and is considered in a separate correction, which accounts for the current consumption and the time since the beginning of the charging sequence. The validity of the ambient data has been widely considered in several iterations of the Smart Citizen Kit, and in V2.1, several other preventive measures have been implemented, aiming to reduce this effect: hardware redesign for better sensor location, and sensor timing. An example of the temperature reading after the charging correction is shown in Fig. 36.

7.3.2. Smart Citizen Station

The ambient temperature in the Smart Citizen Station is obtained from the readings of an external probe, placed 5 cm from the station's body. This probe is based on the Maxim DS18B20, which is chosen for this application for its packaging. The probe is correlated against an external temperature sensor (Sensirion SHT31), showing high correlation results, as shown in Fig. 37 (RMSE < 0.1°C):

Since the external probe only measures temperature, the relative humidity (RH) is calculated using the readings of the Urban Board. Using the definition of relative humidity:

$$RH(pct) = 100\frac{P_{H2O}}{P^{*}_{H2O}}$$

where P_{H_2O} is the partial vapor pressure and $P^{*}_{H_2O}$ is the equilibrium vapor pressure at a certain pressure and temperature. This equilibrium vapor pressure can be determined by the Arden Buck Equation:

$$P^{*}_{H2O} = (1,0007 + 3,46x10^{-6}xP)x6.1121e^{17,520T/(240,97+T)}$$

where P is the absolute pressure in mbar and T is the temperature in °C. Hence, temperature and humidity from the SHT31 on the Urban Board can be corrected with the external probe, using the readings from the atmospheric pressure by the NXP MPL3115A26.

7.3.3. Limitations

As stated above, both the Smart Citizen Kit and the Smart Citizen Station temperature and humidity readings rely on the installation of the device in stable conditions.

Table 11
Temperature and humidity effects in different modes of operation.

Mode	Temperature Effect	Humidity Effect
USB – Publishing over WiFi	~3.3 °C	~-14%rh
USB – Saving in SDCard	~1.3 °C	~-10%rh
Battery – Publishing over WiFi	~1.6 °C	~-7%rh
Battery – Saving in SDCard	~1.2 °C	~-7%rh

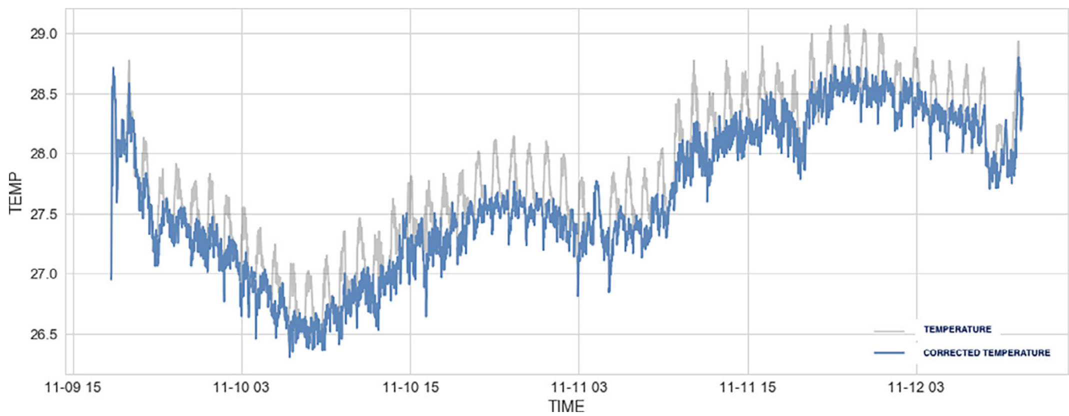

Fig. 36. Temperature correction for charging sequence.

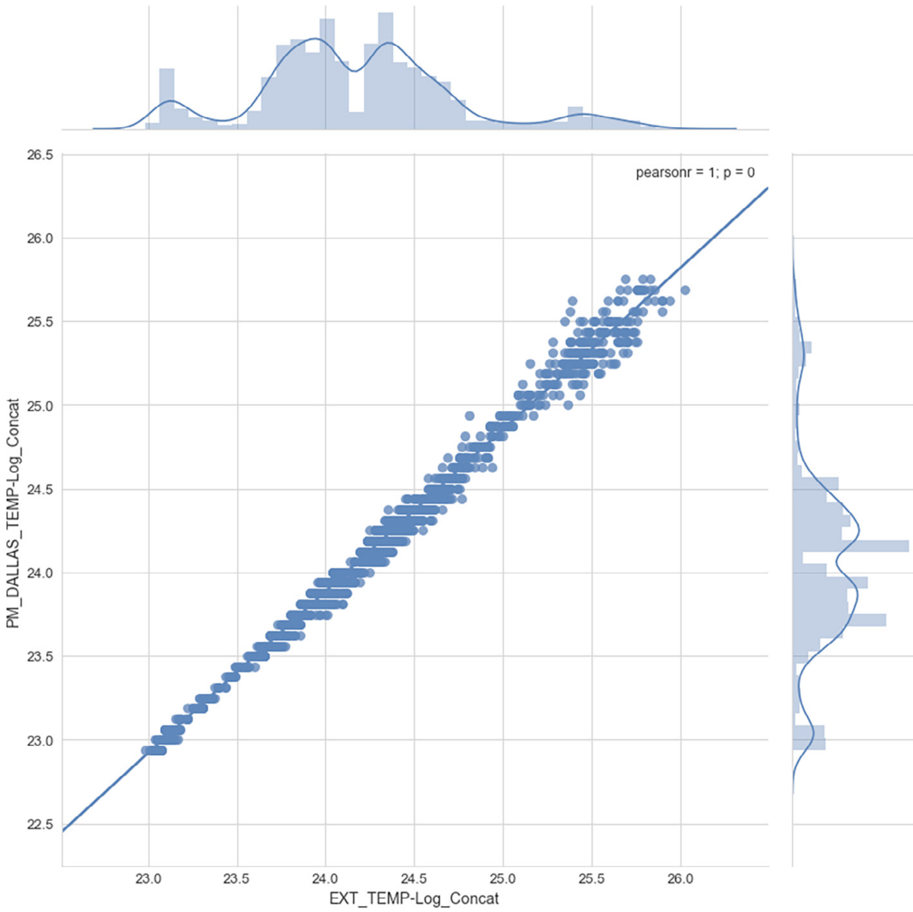

Fig. 37. Temperature correlation for external probe.

The correction algorithm suggested for the Smart Citizen Kit, which aims to compensate for the heating of the electronics and the enclosure effects, is not able to correct for the effect of rapid variable conditions such as intermitent direct sunlight radiation. One solution for this problem would be to use forced ventilation through the Kit, but at the moment of writing this paper, such a solution has not been developed.

In the case of the Smart Citizen Station, the separation between the temperature probe and the Station's body aims to cope with the enclosure heating effect. A dedicated cover is designed, as shown in Section 2, which aims to reduce the effect of direct sunlight radiation.

7.4. Air Pollution Data Validation

The air pollution sensors from the Smart Citizen Kit and Station are undergoing a field evaluation at the moment of writing this paper, as part of the iScape Project mentioned above. The details of this evaluation are specified in the following subsection. Some preliminary results from these tests will be presented, but a full report of this evaluation is not available and will be made public in a subsequent publication. Nevertheless, this section aims to provide potential users with some information about the sensors available, with either test data or references to other available publications.

7.4.1. Sensor Evaluation Campaign

For reference, the test data for the Smart Citizen Station is the result of a sensor evaluation campaign, being carried out at the moment of writing this paper. During this campaign, the Smart Citizen Station V1.0 is deployed in several European cities, shown in Table 12, in co-location with reference equipment and in, at least one of the following conditions: urban background and/or urban traffic.

The objectives of this campaign are: (1) to develop models for sensor calibration under different climatic and pollutant exposure conditions and (2) to assess data quality and compare it with other solutions. This campaign intends to evaluate the Smart Citizen Station, aiming to prevent concerns raised about data quality that other low-cost sensor platforms have shown under scientific testing conditions (Castell et al. [11], Snyder et al. [48] and Lewis et al. [23]).

Table 12
Sites for calibration deployments.

Site	Duration	Conditions	Status
Bologna (Italy)	1 month	Urban Background	Completed – non-valid
Guildford (England)	2.5 months	Urban Background and Traffic	On-going
Dublin (Ireland)	2.5 months	Urban Background and Traffic	Urban Background Completed – valid
Bottrop (Germany)	2.5 months	Urban Traffic	On-going
Helsinki (Finland)	2.5 months	Urban Background and Traffic	On-going
Barcelona (Spain)	1 month	Urban Background	On-going

This evaluation focuses on real-world-conditions calibration, under a wide range of exposure and climatic conditions, rather than developing tests in controlled laboratory conditions, as prior studies show discrepancies in the accuracy resulting from evaluation in these conditions, versus that of outdoor conditions (Castell et al. [11], Spinelle et al. [50]). The tests are conducted by co-location of at least two stations per site alongside additional high-end sensors.

The duration of the tests in each of the locations is a minimum of 2.5 months. This is a compromise between the indications given in [49] for at least 3-months campaign and the availability of high-end sensors for the evaluation. Nevertheless, with this campaign, the authors of this paper intend to cover a range of conditions by the deployment of the Smart Citizen Station in several environments, not only climatic but also in their exposure to various pollutant concentrations. The changes in location are also intended to evaluate how well the sensors can adapt to these exposure and climatic changes [33]. The data is uploaded to the Smart Citizen Platform and is analyzed using the Sensor Analysis Framework. Once the evaluation is done, the results of the testing in terms of models will be uploaded to a dedicated repository [45] and will be implemented on the Smart Citizen Platform for on-the-fly sensor data processing. This processing aims to provide an open platform for sensor analysis using data analysis techniques, the need of which has been highlighted by others in the field (Castell et al. [11], Spinelle et al. [50,51], Sun et al. [52]).

Additionally, it has been noted in the field (Castell et al. [11], Ripoll et al. [33], Philip et al. [29]) that it is necessary to perform individual field calibration for low-cost sensors if measurements comparable to those of high-end solutions are sought. However, this high level of calibration might not always be feasible in a wide range of conditions, leading to non-generalised models which can perform poorly out of the training datasets. This test campaign also aims to study this concern, with an evaluation for a cross-calibration methodology, in which results from a limited subset of observations are applied to the complete dataset, as in Hagan et al. [19]. If successful, this would set the groundwork for the development of calibration strategies where sensors are co-located with high-end sensors and posteriorly deployed for citizen-science activities, in locations where high-end sensors might not be available. This co-location could be performed recurrently, performing sequences of calibration-deployment-calibration, using merging calibrations as suggested in Philip et al. [29].

7.4.2. Analysis per sensor

In this subsection, the results from the electrochemical and particle matter sensors are discussed. Additionally, recommendations and limitations of the system are detailed, as a result of the experience gained from the testing campaign.

For reference, at the moment of submitting this article, the sensor evaluation campaign mentioned in the previous subsection has been completed only on one site, with more than two months of valid data (Dublin, Urban Background). In this site, the pollutants with available reference data are CO, NO2, NOX (hourly average) and PM10 (daily average). Additional data is available for NO2 and CO from the Bologna site, but its validity is questionable, due to the sensor's deployment conditions. In both of these sites, the results shown are from the Smart Citizen Station V1.0, without the redesign shown in Section 2 of this article.

7.4.2.1. Electrochemical sensors. The Smart Citizen Station uses three Alphasense Ltd. 4-electrode electrochemical sensors, measuring Carbon Monoxide (CO), Nitrogen Dioxide (NO2) and OX (Ozone + Nitrogen Dioxide). The NO2 and OX sensors are used together, and after the data is gathered, post-processing is used in order to de-convolve the Ozone and NO2 in the OX sensor, using the readings from the NO2 sensor. The maturity of this processing is not robust at the moment of submitting this paper, and for this reason, Ozone results are not discussed. On the other hand, CO and NO2 results will be discussed from the test sites in Dublin and Bologna.

The results from January 2019 in Dublin show a very high correlation ($R^2 > 0.8$) and low error (RMSE < 0.1 ppm) in the CO measurements, during more than two months of deployment. The sensor behaves linearly with respect to the target pollutant concentrations and its decay during this period is negligible. Results from this campaign are shown in Figs. 38 and 39, both from the Dublin site. Additionally, sensor cross-correlation (between both CO sensors on the Smart Citizen Station) also show $R^2 > 0.7$ (shown in Fig. 40). In this Figure, one of the devices suffered power supply concerns, therefore its data has been eliminated from the analysis.

NO2 results from the Dublin site show a high correlation in conditions over 15 ppb of NO2. In urban background conditions, however, this condition is not easily achieved, and hence the correlation between the reference equipment and the NO2 sensor drops to $R^2 = 0.4$, with RMSE = 0.12 ppb. As seen in Figs. 41 and 42, the sensor baseline is at 15 ppb, and does not show the same linear behaviour as the CO sensor data above.

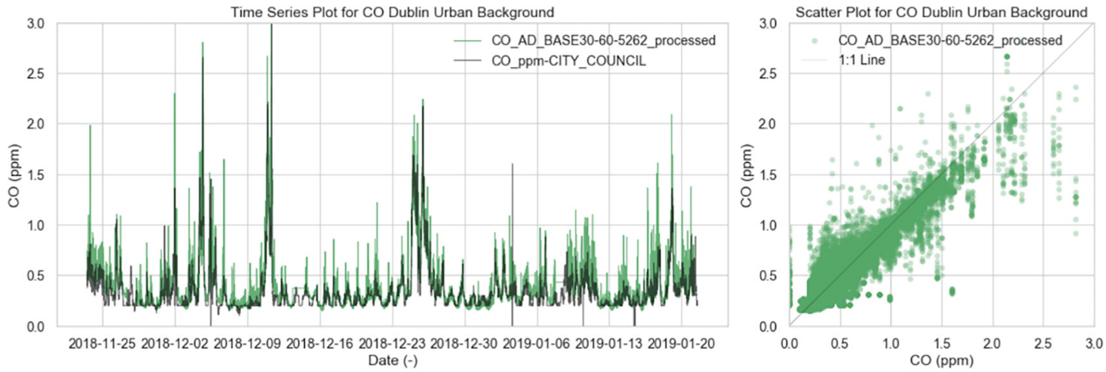

Fig. 38. CO results from Dublin Test – Winter 2018–2019, Smart Citizen Station V1.0. RMSE = 0.08 ppm, R^2 = 0.9. No model correction applied. Green: Smart Citizen Station/ Black: reference equipment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

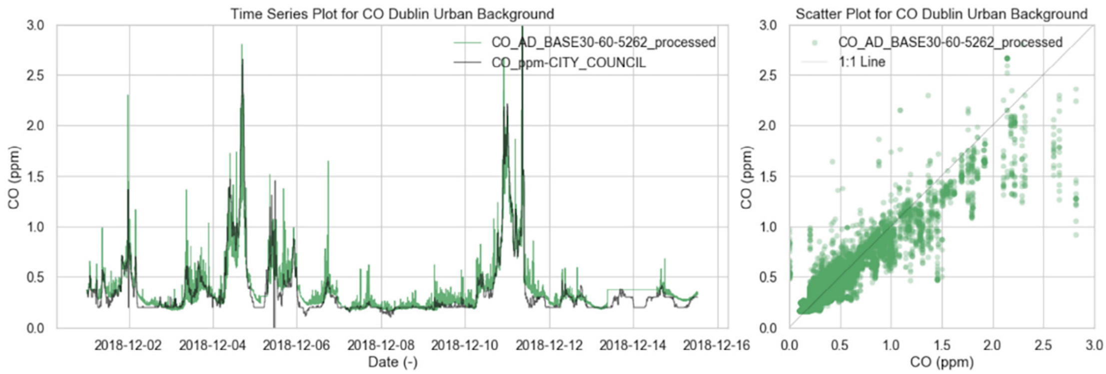

Fig. 39. CO results from Dublin Test – Winter 2018–2019 (zoomed), Smart Citizen Station V1.0. RMSE = 0.08 ppm, R^2 = 0.9. No model correction applied. Green: Smart Citizen Station/ Black: reference equipment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

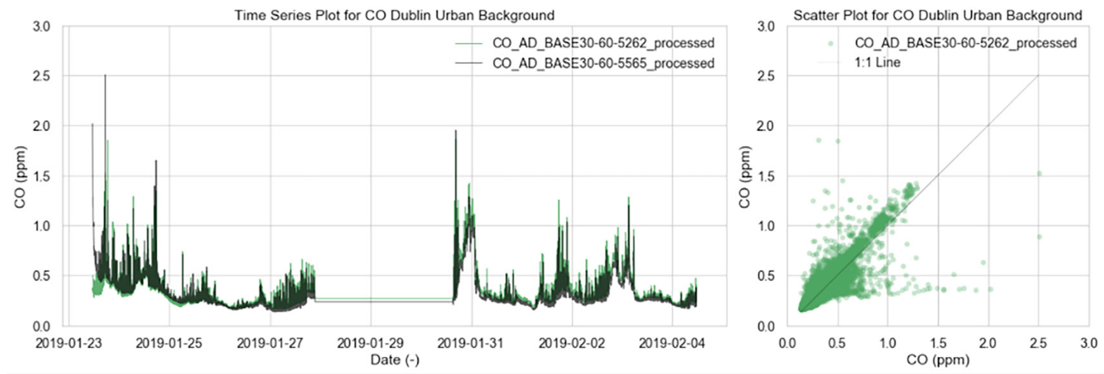

Fig. 40. Cross-correlation of CO results from Dublin Test – Winter 2018–2019, Smart Citizen Station V1.0. $RMSE = 0.06ppm, R^2 = 0.75$. No model correction applied. Green: Smart Citizen Station 1/ Black: Smart Citizen Station 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Additionally, results from the Bologna site with the Smart Citizen Station V1.0, show the effect of rapid temperature changes on the Smart Citizen Station. At this site, the absence of a cover to protect the device from direct sunlight, affected the sensor behaviour as shown in Fig. 43. This effect has been addressed in the V2.0 of the device by: (1) reducing the thermal mass and (2) adding a rain/sun cover shown in Fig. 26. Results of the second iteration are not included in this article, as it has not been deployed for sufficient time at the time of this publication.

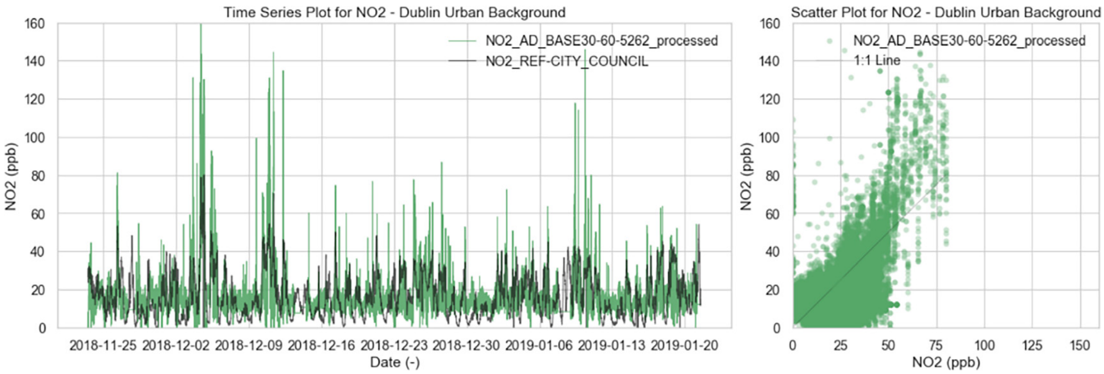

Fig. 41. NO2 results from Dublin Test – Winter 2018–2019, Smart Citizen Station V1.0. RMSE = 0.12 ppb, R^2 = 0.4. No model correction applied. Green: Smart Citizen Station/ Black: reference equipment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

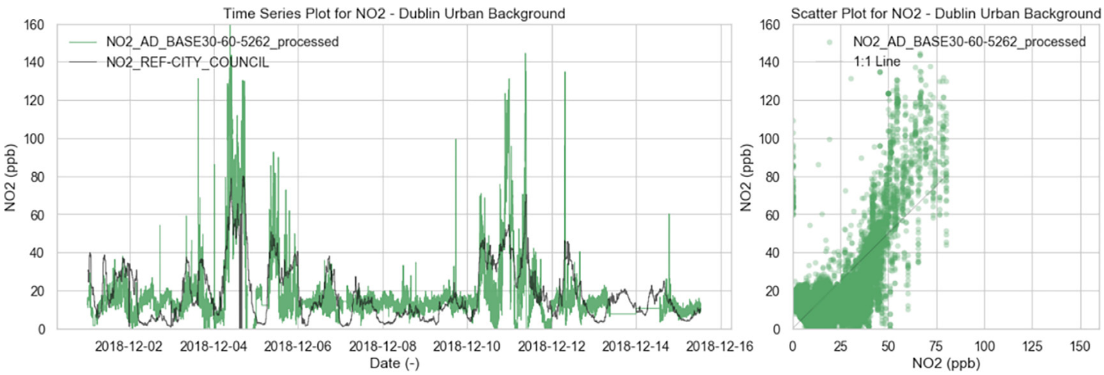

Fig. 42. NO2 results from Dublin Test – Winter 2018–2019 (zoomed). RMSE = 0.12 ppb, R^2 = 0.4. No model correction applied. Green: Smart Citizen Station/ Black: reference equipment.

These results can be improved through the application of statistical models to account for ambient conditions and temperature transients. An example of this processing can be seen in Fig. 44, from the Dublin site, increasing R^2 to 0.6 and reducing the RMSE to 10 ppb:

To conclude, the results from CO electrochemical sensors shown in this article demonstrate the strong performance of the sensor in the conditions tested. NO2 and OX sensors require further testing in order to improve model quality and derive sensor limitations. These tests are already planned as part of the iScape project. Results from other authors show that sensor performance can be improved (Hagan et al. [19], Popoola et al. [27]). In order to assess this, in line with the objectives of the sensor evaluation campaign mentioned above, further deployments in higher pollution areas are being conducted. These results will be made public in a measurement oriented publication upon completion.

7.4.2.2. PM sensors. The PM sensors available in the Smart Citizen Kit (one sensor per Kit) and the Smart Citizen Station (two sensors per Station), are the Plantower PMS5003 sensor. These sensors are used in Purple Air solution [32] and have been evaluated by the South Coast AQMD (Air Quality Management District), USA, giving results for PM10 and PM2.5 with high correlation results with respect to reference equipment ($R^2 > 0.9$ in most cases) [17]. In Sayahi et al. [34], the authors also show strong results and recommend the usage of these sensors, although in some measurement conditions they perform better than in others, as discussed below.

The only available results from the sensor evaluation campaign up until the date of publication are shown in Fig. 45, which compares PM10 on an urban background environment, at the Dublin site. These results provide a daily average, showing a strong preliminary correlation, but there is insufficient data at this time. More data will be obtained during the duration of the sensor evaluation campaign.

The PM sensors used are nephelometers. These sensors measure suspended particulates by employing a light beam (source beam) and a light detector set at a 90° angle to the source beam. Particle density is then a function of the light reflected into the detector and the particle mass is a calculation derived from this density, assuming certain properties of

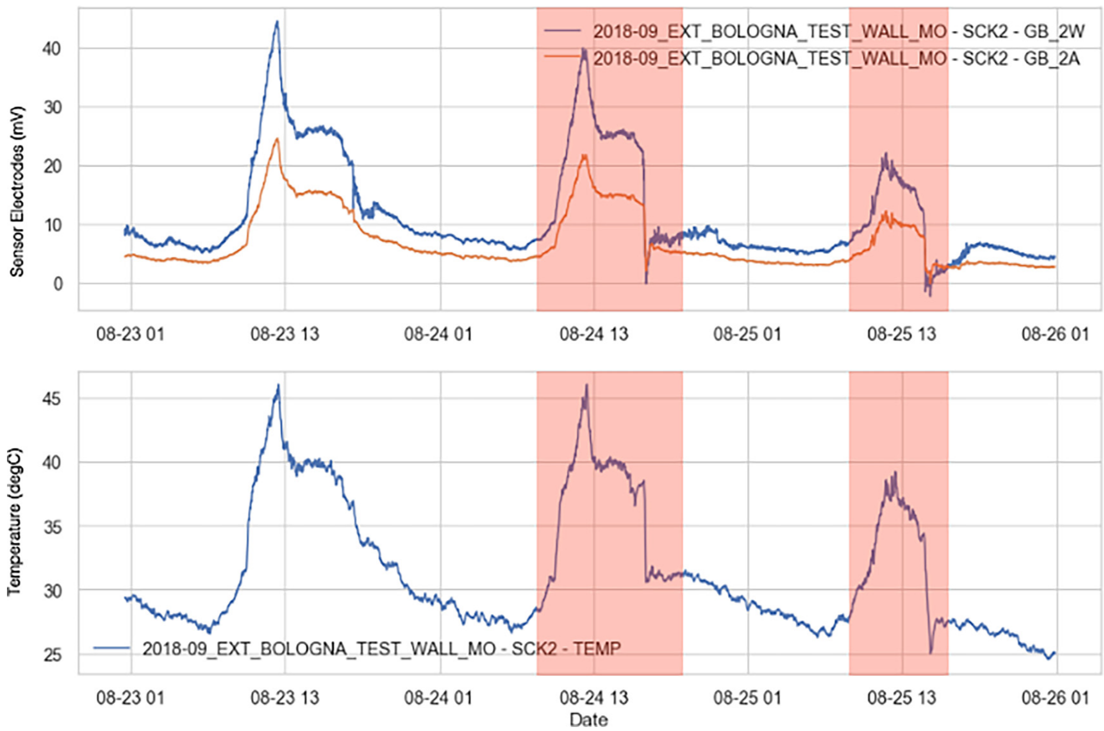

Fig. 43. NO2 results from Bologna Test – Summer 2018. Effect of temperature transients on measurement stability.

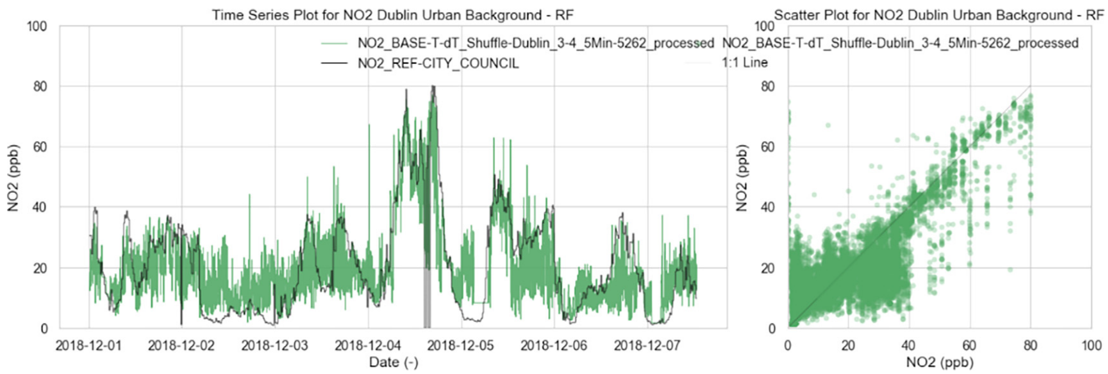

Fig. 44. NO2 results from Dublin Test – Winter 2018–2019. RMSE = 0.10 ppb, R^2 = 0.6. Model correction applied. Green: Smart Citizen Station/ Black: reference equipment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the particles, such as shape, color and reflectivity, among others. Relative humidity affects this type of sensor, since particles can absorb water and grow in size, hence modifying the fractions and the calculated mass. Additionally, a particle's chemistry can affect these assumed properties, and these assumptions may not be usable in every environment (Di Antonio et al.) [13]. However, a relative humidity correction is being tested using the approach described in Di Antonio et al. [13], correcting size distribution based on particle higroscopicity.

Declaration of Competing Interest

Seeed Studio, a manufacturer and online seller of open hardware, commercially sells a version of the described hardware. A percentage of the sells generated income goes to IAAC Fab Lab Barcelona to support the future project development and maintain the software platform.

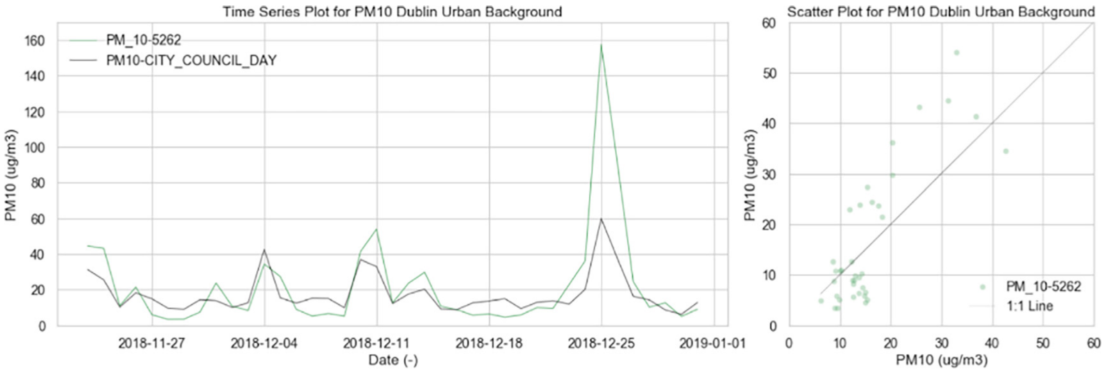

Fig. 45. PM10 results from Dublin Test – Winter 2018–2019. RMSE = 19 μg/m^3, R^2 = 0.8. No model correction applied. Green: Smart Citizen Station/ Black: reference equipment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Acknowledgments

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Appendix A. Annex

A.1. Repositories

Camprodon, Guillem; Barberan, Victor; Bizzotto, Alejandro; Gonzalez, Oscar; Posada, Alex (2019), "Smart Citizen Gases Pro Board", Mendeley Data, v2.

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Camprodon, Guillem; Smari, Viktor; Rees, John (2019), "Smart Citizen Platform", Mendeley Data, v2.

https://doi.org/10.17632/32mhpj369n.2

Gonzalez, Oscar; Camprodon, Guillem; Barberan, Victor (2019), "Smart Citizen Sensor Analysis Framework", Mendeley Data, v2.

https://doi.org/10.17632/2c8zyntkjg.2

Camprodon, Guillem; Perez, Maximo; Barberan, Victor (2019), "Smart Citizen PM Board", Mendeley Data, v2.

https://doi.org/10.17632/ztw2z2p28h.2

Camprodon, Guillem; Barberan, Victor; Perez, Maximo; Gonzalez, Oscar; de Heras, Miguel Angel; Smari, Viktor (2019), Smart Citizen Kit 2.1, Mendeley Data, v1.

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Camprodon, Guillem; Smari, Viktor; Somers, Dorian (2019), "Smart Citizen Web Front End", Mendeley Data, v1.

https://doi.org/10.17632/587gjmcsk3.1

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, athttps://doi.org/10.1016/j.ohx.2019.e00070.

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