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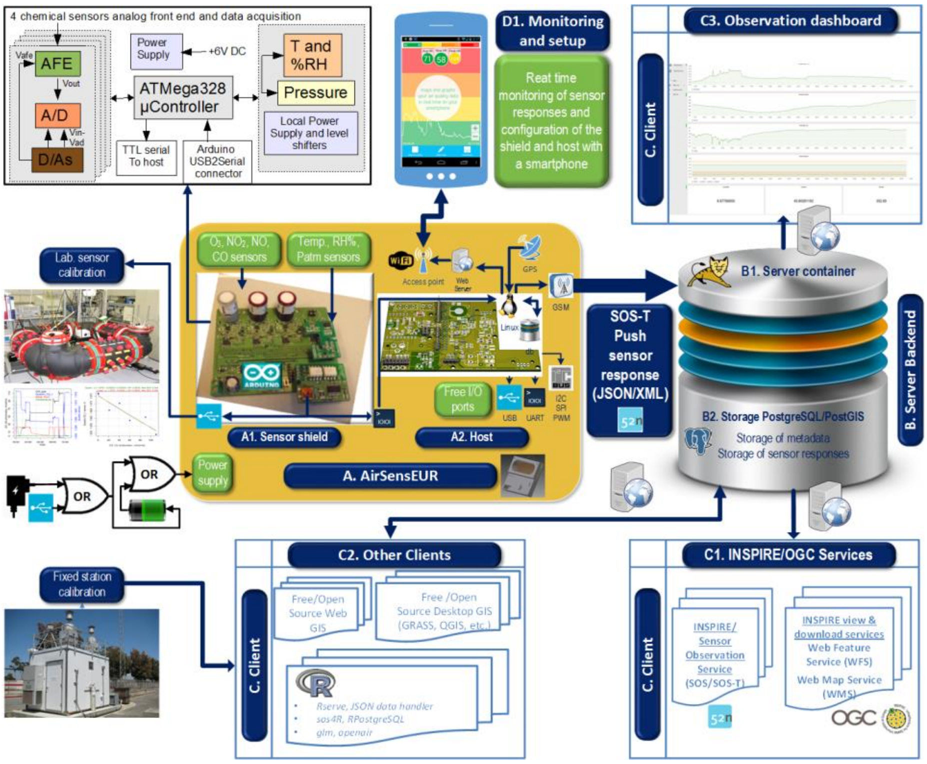

AirSensEUR: an open data/software /hardware multi-sensor platform for air quality monitoring. Part A: sensor shield

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Abstract
The use of mobile low cost sensors for regulatory purposes or citizen observatory projects is quickly developing. Although several sensor systems have appeared the last years, generally developers cannot tackle the whole set of open problems regarding their use and the accuracy of the information they provide. Currently air pollution using low cost sensors involves fast growing private companies and/or public institutes specialized in digital technologies. Unfortunately, a great deal of effort is wasted by repeating the same research by several private companies/public institutes or within several European projects. Moreover, when a technological solution is found, it is generally subjected to confidentiality aspects of the intellectual property right.
In order to facilitate the use of sensors by diminishing the operational and development costs, the Joint Research Centre is developing a multi-sensor platform, called AirSensEUR, for the monitoring of air pollution at low concentration levels. All development aspects owned by JRC about AirSensEUR is made available to all stockholders though the use of public licenses. AirSensEUR is developed as an open software/open hardware object that has the capacity to behave as a node within a network of multi sensors assuring interoperability and compliance with the INSPIRE Directive.

Executive summary

The issue of using mobile low-cost sensors by local authorities, laboratories in charge of air quality monitoring for regulatory purposes or by citizens is quickly developing. Several sensor systems have been developed in the last years by fast growing private companies and/or public institutes specialized in digital technologies. Unfortunately, these sensors do not give satisfaction for all desired functionalities including the measurement accuracy of the sensor systems, the localization and identification of the micro-environments being sampled and the reporting of these data in order to make them available to all stakeholders through the Web services. Moreover, a great deal of effort is wasted by repeating the same research by several companies/institutes or within research projects. Additionally, new technological solutions that may be found are generally subjected to confidentiality of the intellectual property rights preventing them to be widely applied.

In order to facilitate the use of sensors by diminishing the operational and development cost, the Joint Research Centre (JRC) is developing a multi-sensor platform, called AirSensEUR, for the monitoring of air pollution at low concentration levels with low-cost sensors. JRC makes all development aspects about AirSensEUR freely available through the use of public licenses. In fact, AirSensEUR is developed as an open software/open hardware object that has the capacity to behave as a node within a network of multi sensors assuring interoperability and compliance with the INSPIRE Directive (Infrastructure for Spatial Information in the European Community).

The JRC objective was to build both the AirSensEUR host platform able to connect with several sensor shields to be later developed and to develop the first sensor shield for air pollution sensors. The sensor shield is connected to the host in charge of collecting the measurements. The host supplements measurements with geographical coordinates and it sends data to a public database on the web where mapping and query services are available.

This report describes the sensor shield while the AirSensEUR host will be presented in another EUR report. The electronic diagrams of the shield are given together with a firmware for the micro-controller, a Java Front End panel to easily configure all the sensors and a protocol to exchange data through a serial communication port between the shield and the host or any other controller with a COM to USB port. The shield consists of an electronic board with 4 sensor channels and a deported board with temperature, relative humidity and pressure sensors. Many models of 2-electrode and 3-electrode amperometric sensors can be mounted on AirSensEUR. The shield can accommodate sensors of Alphasense, City Technology, Membrapor and SGX Sensotech, the major manufacturers of this type of sensors.

A laboratory evaluation of the performances of Sensoric-City Technology sensors fitted on the AirSensEUR shield is also reported. For this evaluation O_3, NO_2, NO and CO sensors were mounted on this shield. The experiments carried out in laboratory showed that AirSensEUR is easy to configure and sensitive enough to measure ambient air pollution in the range expected at background and traffic sites placed in rural, urban and suburban area. However, a solution for the interference between O_3 and NO_2 and a correction for the temperature dependence of the City Technology sensors shall be developed as for example an active sampling system including an O_3 and NO_2 filtering module mounted on the sensor shied.

AirSensEUR is a promising technology for the monitoring of air pollution at fixed sites and for population exposure in mobile context at low cost.

Contents

1 Introduction

The use of low-cost sensors by laboratories in charge of ambient air monitoring for regulatory purposes or by citizens is quickly developing. At the same time, low-cost sensors raise strategic questions including the assessment of the quality of the information provided by those devices, the localization and identification of the micro-environments being sampled and the automatic reporting of this information so that it is available for all stakeholders using near to real time web services.

Although several sensor systems have appeared in the last years, generally the developers do not have the capacity to tackle the whole set of open questions regarding sensor systems. Currently air pollution using low cost sensors involves fast growing companies and/or public institutes specialized in digital technologies. Unfortunately, a great deal of effort is wasted by repeating the same research by several companies/institutes or within research projects. Moreover when a solution for one of the problem listed above is found, it is generally subjected to the control of the intellectual property rights.

In order to facilitate the use of sensors by diminishing the operational and development cost, the Joint Research Centre (JRC) is developing a multi-sensor platform, called AirSensEUR, for the monitoring of air pollution at low concentration levels. All development aspects owned by JRC about AirSensEUR are made freely available through the use of public licenses. AirSensEUR is developed as an open software/open hardware object that has the capacity to behave as a node within a network of multi sensors assuring interoperability and compliance with the INSPIRE Directive [1]. We strongly believe in such a common and participative plan for the establishment of a scientific community both of interested users and/or developers joining forces to build a validated sensor system.

The JRC objective is to build both the AirSensEUR host platform able to simultaneously control several sensor shields and to develop the first sensor shield for air pollution sensors to be connected to the host.

The host integrates functionalities shared by sensor shields including GPS positioning, Linux operating system and programming languages to control a list of I/O ports used by the shields (COM, USB, SPI, I2C, PWM …) with sufficient RAM, CPU computing capacity and a micro-SD storage up to 64Gb. Twined with the host platform we designed the 1^{st} AirSensEUR sensor shield for air pollution monitoring based on electrochemical sensors. Figure 1 gives the flow chart of the AirSensEUR platform with the whole set of functionalities that is planned to develop.

The development of the sensor shield (block A1) is now complete (version 2.2). The host is in its final development state. The final version is expected to be available in fall 2015. We have started designing 2 handling boxes, one for the host and one for the shield. We expect that the CAD files could be available at the end 2015 and distributed under public license. The laboratory evaluation and calibration of the sensor shield was carried out for the O_3, NO_2, CO and NO City Technology sensors (block A3). More evaluation should be carried out in particular for filtered or other more sensitive sensor brands and models. However, these tests are not currently planned.

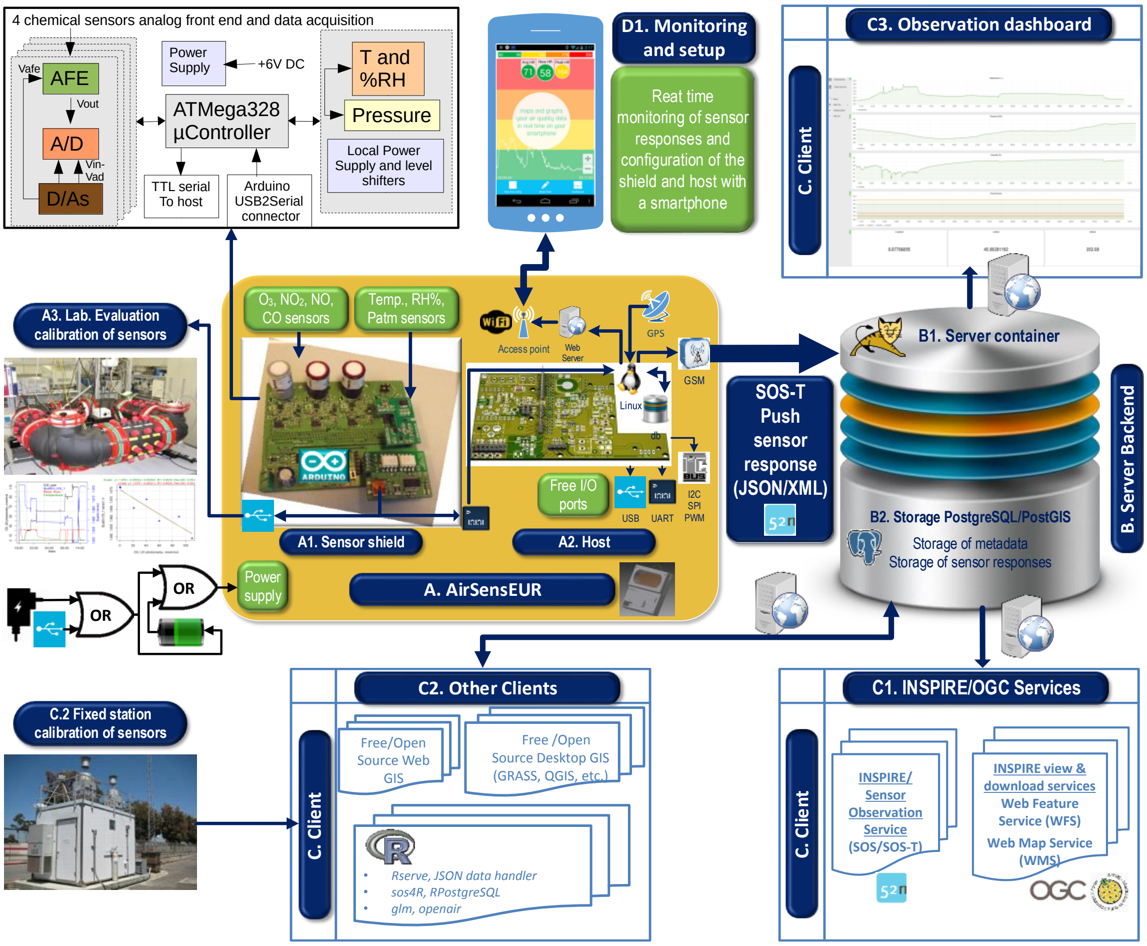

Figure 1: Schematic diagram of the AirSensEUR platform

The data transfer to a server backend (blocks B1 and B2) has been developed in compliance with the requirements of the INSPIRE Directive [1] using the Sensor Observation Services SOS interface standard [2] and it is in validation stage. The remote transfer functionalities of AirSensEUR will be published in the host report together with a cook book for the configuration of the backend server.

The architecture of AirSensEUR based on well-established free and open source software, also includes an Inspire view (through a Web Map Service - WMS), download services (block C1) and the web observation dashboard (block C3) that gives the possibility to visualize time series plots of data stored in the PostgreSQL database (block B) need be developed though they should require limited effort to be set up.

The block C2 in Figure 1 is about the development of algorithms for the correction of sensor measurements based on the reference measurements of automatic stations or using the results of laboratory experiments in exposure chamber (block A3). Other possibility as the chemical filtering of interference and on-board calibration possibilities will be studied. The final solution of this module is expected to be ready in the 2nd half of 2016.

The host will have the capacity to act as an access point for a short time in order to save the battery autonomy. A local web server will be created on the host allowing configuring each sensor channel data acquisition and monitoring the sensor shield responses and the data stored in the host data base (block D1). The web server and access point still have to be developed. It is planned to be available in the first half 2016.

The addition of other functionalities as for example building a smartphone app for the near-to-real-time mapping of AirSensEUR observations, automatic detection of indoor/outdoor location, estimating population exposure based on data in the server backend database are currently discussed.

This report presents the sensor shield (block A1) and the results of sensor tests (block A3). The host platform will be presented in another EUR report likely at the beginning of 2016.

2 Copyright notices

The AirSensEUR shield consists of electronic diagrams, a firmware and a JAVA software, a list of components and a communication protocol. The electronic diagrams, the firmware and the JAVA software are released under Public License. The diagrams and software can be downloaded at: ftp://ftp-ccu.jrc.it/pub/gerbomi/AirSensEUR and http://www.airsenseur.org/. In case the FTP site would be deleted you are kindly suggested to contact by mail one of the authors.

2.1 Electronic diagrams

The electronic diagrams of the gas sensor shield, the board for temperature, humidity and pressure and the COM-to-USB board are distributed under the Creative Commons Attribution Share Alike Attribution, the CC BY SA 4.0 International (see 9). This license lets others remix, tweak and build upon the work being done even for commercial purposes, as long as credit is given as stated here below. New creations (any new works based on the current one) shall be licensed under the identical terms, so any derivatives will also allow commercial use. Additionally, any adaptation/improvement by third parties shall also be made available under the same license preventing from private appropriation of improvements. The copyright notice is as follows:

2.2 Software

The firmware and the JAVA software developed for the AirSensEUR shield are released under the European Public License, an open source license for software. The copyright notice is as follows:

Licence

Date: 02/04/2015

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3 Technical description of the AirSensEUR shield

The AirSensEUR shield is a multi-sensor platform developed starting from the results of the MACPoll project ([3]–[7]). In developing the shield, the following objectives and functionalities of the shield were considered:

- to be able to manage 4 gas sensors consisting of 2/3 electrode sensors. Lately, a modification of the Printed Circuit Board (PCB) has allowed the use of different brands and models of sensor (see 4.1).
- to include auxiliary measurement for temperature, relative humidity and pressure. These parameters would be used both for information and they could also be used in correction algorithms of the sensor responses.
- to reach high accuracy and high resolution for the sensor responses.
- to build an open software/open data object
- to allow the configuration of each sensor channel in a simple way (without reprograming).

Keeping these objectives in mind, we adopted the following technical solutions listed in the same order as the list of objectives:

1. amperometric sensors were found convenient taking into consideration the low electronic noise and the ease of operation of these type of sensors. We selected the NO2 3E50 for nitrogen dioxide, O3 3E1F for ozone adding the NO 3E100 for nitrogen monoxide and CO 3E300 for carbon monoxide form City Technology though other brands are available (Alphasense, City Technology, Membrapor and SGX Sensortech (see 9.3).
2. for temperature, relative humidity and pressure, two sensors (a Sensortech UR100CD for temperature and relative humidity and a Bosh BMP180 [8] for pressure) are mounted on small PCB that can be directly connected on the shield or can be connected with long wire.
3. the electronic circuitry was optimised to avoid temperature drift. We tried to balance the component prices with the selection of high quality electronic components in order to improve the stability and reduce electronic noise. Each sensor channel is composed of a fully programmable Analog Front End (AFE) with a dedicated Integrated Circuit. Regarding the electronic resolution, for each channel, a 16 bit analogic-to-digital converter (ADC) was used in conjunction with a digital-to analogic converter (DAC). The DAC is used to set the limit of the ADC. In this way, even little change in signal can be detected, as the ADC resolution reach the µV range.
4. all electronic schemes and software are published under public license (see 9). The diagrams and software allows using the major part of the 2 and 3-electrode sensors currently available on the market (see 4.1). We also give the Bill of Materials (BOM, see 9.2) and a communication protocol allowing to use of the shield with any controller including a

COM port (see Appendix 9.4). However, the PCB diagrams are not published as they are the property of LiberaIntentio[1]. For the micro-controller of the shield, we chose an ATMega328 Atmel CPU [9] that allows the use of the open Arduino environment [10], [11] for programming and uploading of the firmware. The micro-controller interoperates with the signal processing (ADC and DAC), retrieves the digital samples of each sensor and transmits raw signals to the AirSensEUR host board (an Arietta G25 from ACMESystem-IT [12]). Any similar rapid controlling system could be used through a serial line.

5. a JAVA control panel allows configuration of the Analog Front End (AFE) of each sensor. It offers the possibility to independently optimise the bias potential, load resistance, and sensitivity parameters. It is also used to set up the filtering of electronic noise and the averaging time of each channel. The Java Front End directly sets up the shield micro-controller that interoperates with the signal processing system (ADC, DAC and AFE).

3.1 Shield

The architecture of the sensor shield is given in Figure 2. The left block represents the gaseous sensor interface. It is composed of a fully programmable Analog Front End (AFE, TI LMP91000, Texas Instruments, US [13]), a 16-bit A/D converter (TI ADC16S626 [14]) and a 12bit D/A converter (AD5694RB). The D/A converter is used to dynamically set the range of the A/D converter in order to keep its resolution in the sensor output range. It has been added during the development of the shield in order to allow keeping a good resolution when acquiring very low voltages. The best resolution of the data acquisition reaches 15.3 µV when the board is set to a full range of ±0.5V taking the 16 bits of conversion of the ADC into account. As the sensors give a change of 0 and 10 mV for NO2 and SO2 in the 1000 ppb range, the sensor board resolution is well consistent with the sensitivity of the sensors and range of pollutants in ambient air.

The right block includes of a block containing two digital sensors: one for both temperature and relative humidity measurements (UR100CD see 5) and one for pressure measurements (Bosh BMP180 [15]), together with the needed power supply and an I2C level shifters to interface to the micro-controller. The level shifter is used to shift the voltages of the bus signals so that devices of different voltages can communicate over the same bus of the micro-controller [16].

Finally the central element consists of a micro-controller ATMega328 [9]. It's in charge of properly setup both the analog front ends of the 4 chemical sensors, the A/D and D/A registers and the external sensors (temperature, humidity, pressure). It also retrieves, filters and averages the responses of the seven sensors and concatenated all of them into a hexadecimal string. The microcontroller provides a serial line which is used to interface with the external host. The ATMega328 can receive a firmware by the onboard serial connector through an USB to Serial adapter compatible with the Arduino framework and integrated development environment (IDE).

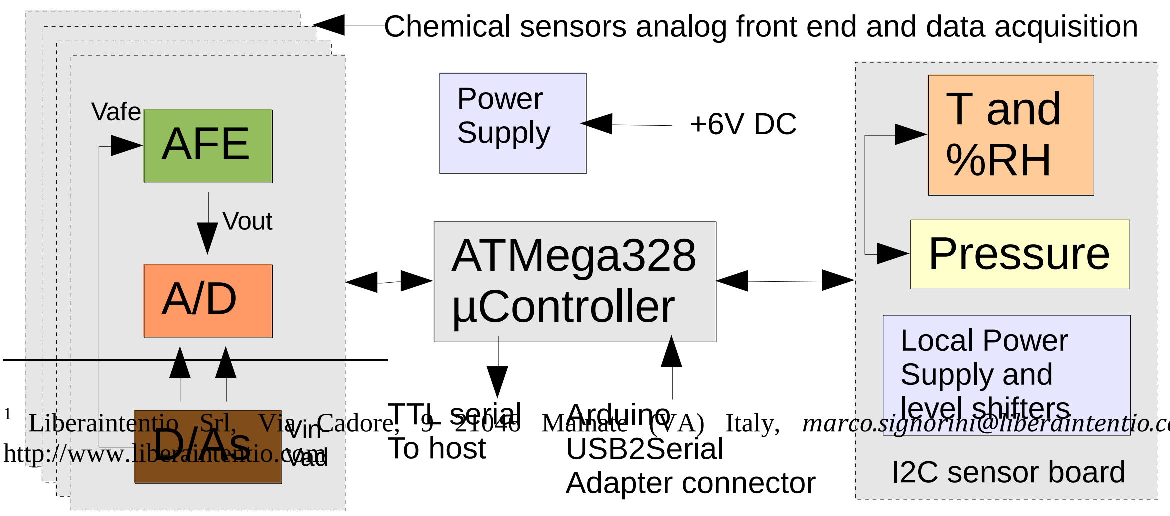

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Figure 2: Block schematics representation of the sensor shield

An USB board (USB2Serial see diagram in Appendix 9.1) plugged on the shield allows real-time data acquisition of the data for example for laboratory calibration without the need of the AirSensEUR host. Additionally, a communication protocol and a JAVA control panel has been developed in order to easily configure the AFE of each channel (sensor voltage, D/A outputs, A/D conversion limits, gain, load resistance of each sensor -RL, bias, IIR filtering [17], DAQ periodicity and averaging time) and read sensor responses. All the above mentioned parameters are explained in the section 3.2 below.

The shield was designed with:

- 4 programmable high precision three leads chemical sensor AFE [13]
- 4 high precision 16 bit A/D converters [14]
- 4 12bit D/A converters (AD5694RB)
- a ATMega328 processor running at 16MHz [9]
- a linear power supply regulators
- a single 6V power supply, polarity protected
- an opto-coupled USB2Serial acquisition board

In order to keep the resolution of the 16 bit of A/D converter in the useful range of sensor outputs, a 12bit D/A converter (AD5694RB) was included before the AFE and the sensor. In that way the range of the sensor response can be pre-set and the quantum resolution of the A/D converter (16 bit) is kept undivided. Each D/A converter is able to generate 3 analogue voltages used as references by both A/D converter and AFE. Figure 3 shows the logical scheme of one sensor channel with the D/A converter (bottom) which generate the 3 reference voltages (VOA, VOB and VOC) used by the A/D converter (VOA and VOB) and by the AFE (VOB and VOC).

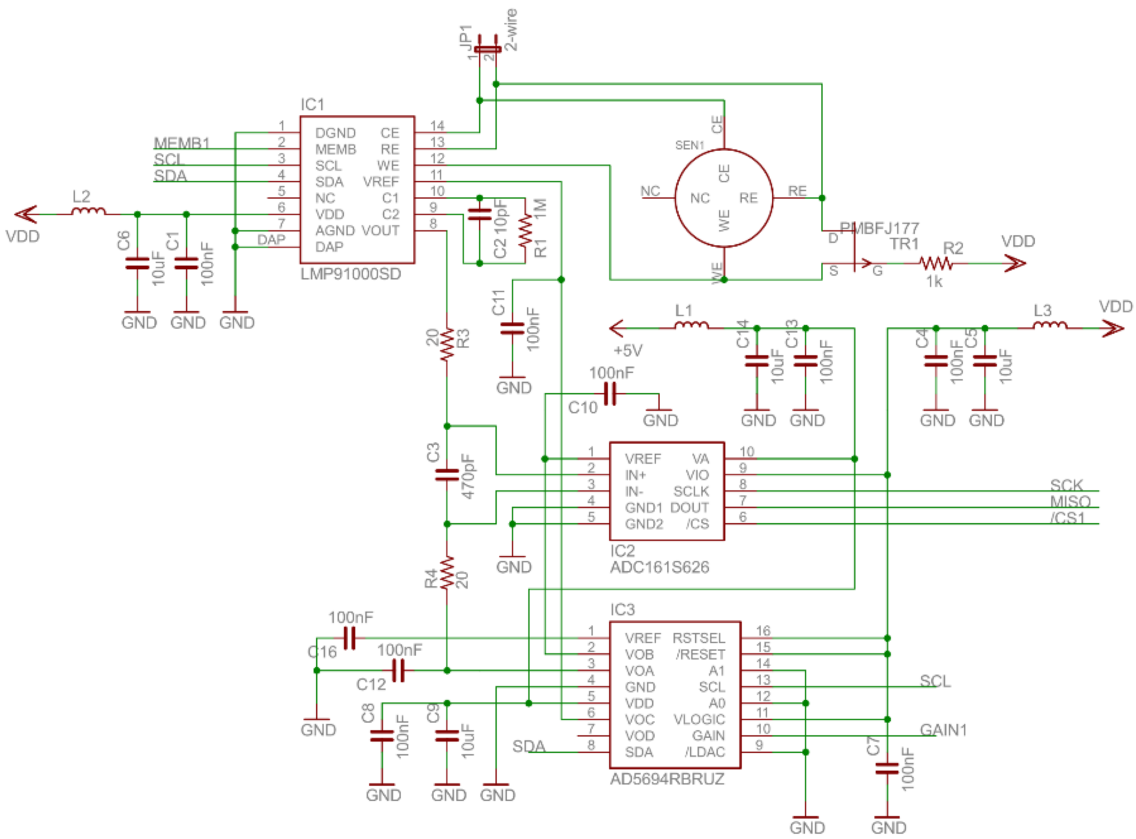


Figure 3: Logical scheme of one sensor line (see Appendix 9.1)

The shield is also equipped with a daughter board in order to measure temperature, relative humidity using a UR100CD sensor (see Appendix 9.2.3) and pressure sensors using a Bosh BMP180 sensor [15]. The Appendix 9.1 shows the schematics of this daughter board. The digital sensors are factory calibrated and operate through I2C digital bus. The UR100CD sensor monitors temperature with an accuracy of ± 0.3°C and relative humidity with an accuracy of ±2%. The Bosh BMP180 has a typical absolute accuracy of 0.1hP and a resolution of 0.01hP. Both sensors were selected because of their high sensitivity and high accuracy with low power consumption. The responses of these sensors being digitized, they do not suffer interference from temperature, electromagnetic fields etc… when used in field. Equation 1, Equation 2 and Equation 3 are used to transform response signals into temperature in °C, relative humidity in % and atmospheric pressure in hPa.

Temperature: $$T = \left(\frac{T_s \times 165}{16384}\right) - 40$$ ***Equation 1***

Relative humidity: $$RH = \frac{RH_s \times 100}{16384}$$ ***Equation 2***

Pressure: $$P = \frac{P_s}{48}$$ ***Equation 3***

Figure 4 shows the logical scheme of the microcontroller of the shield and the interface with the 4 sensors channels. The micro controller is the ATMega328 Atmel microcontroller [18]. It operates at 16MHz and is factory programmed with optiboot [19]. This solution grants a complete compatibility with the Arduino platform allowing users to easily implement a custom firmware through the Arduino IDE [10]. The communication between the shield and the computer through using a dedicated slot for an external Arduino USB2Serial programmer [20].

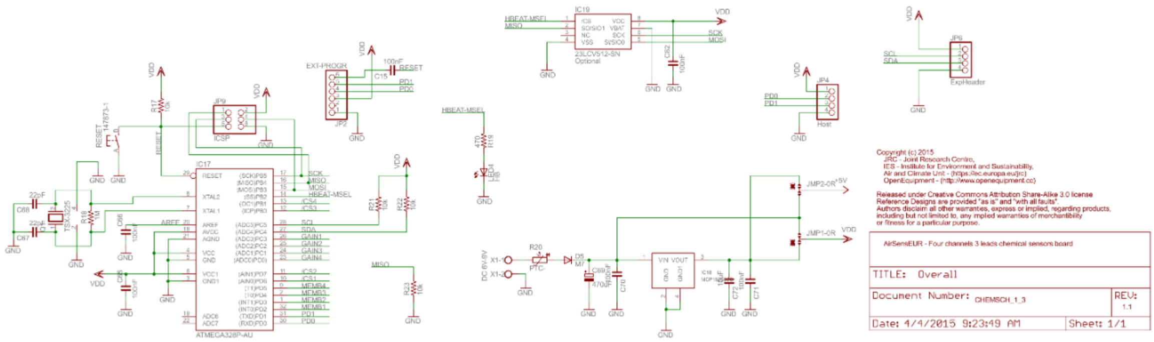


Figure 4: logical scheme of the micro-controller and connection to the 4 sensors (see Appendix 9.1)

An additional USB2Serial acquisition board was also developed for calibration purpose. To avoid electronic noise interaction, especially from the different ground, this board mounts side by side 2 opto-coupler used as an isolating system (see Appendix 9.1). This is particularly useful with the low voltage expected with the selected sensors. Both samples and configuration commands are exchanged with an external host through this USB2Serial acquisition board using a TTL serial interface. These tasks can also be done using a commercial USB2Serial programmer. However, as the data communication lines (serial Tx and RX) are shared between the USB2Serial acquisition board and the USB2Serial programmer, the shield must be disconnect from USB2Serial acquisition board and power supply in order to upload new firmware in the ATMega328 through the USB2Serial programmer.

3.2 Software

3.2.1 Firmware

A few parameters of the analogic and digital sensors are configured using the USB2Serial acquisition board. Once set up, they are saved in the non-volatile memory embedded on the ATMega328. When powering up the shield or after a reset, the microcontroller reads all the coefficients from the non-volatile memory and automatically sets up the hardware.

With a periodicity set by the user, a custom firmware samples the sensors, performs a set of basic statistical operations then mark samples with a progressive timestamp. Figure 5 shows the flow chart of the firmware logic that thrives to minimize the ATMega328 calculation load. The process is applied to the 7 sensors of the shield. In this figure, IIR stands for Infinite Impulse Response filter [17]. Below are the different parameters that can be set and the related action performed by the firmware:

- Sampling rate of sensors, entered as ticks corresponding to a periodicity in of 10 ms. The sampling frequency is Fs = 1/Periodicity of measurements.
- Two different Infinite Impulse Response filters are applied using 2 different filter coefficients.
- Decimation filtering, called Ratio, is used to discard samples in order to limit the CPU load in case of wide moving average (see below). The ratio of the decimation filter is used to discard samples based on the Ratio parameter. The output of the decimation filtering consists of Fs/Ratio samples per seconds.
- The Moving average, with size called Length corresponding to the number of data after decimation that are averaged. This moving average filter releases data at the rate of Fs/(Ratio*Length) samples per seconds.
- The output data is timestamped before being stored on a temporary buffer to be read by an external host

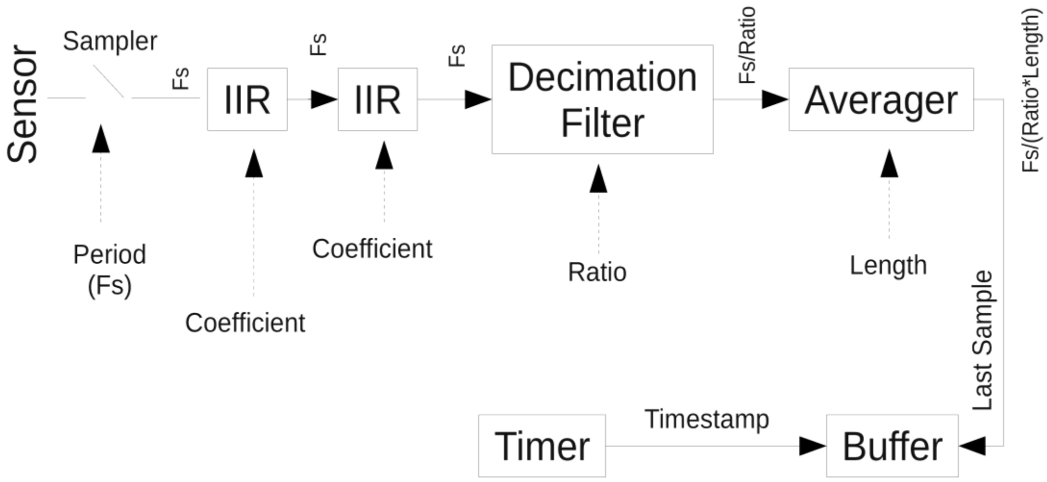


Figure 5: Flow chart of the firmware logic

More details of the setting of the firmware and parameters are given below (3.2.2). The solid arrows on Figure 5 mark data flow direction. The external host sends appropriate commands to the Arduino controller over the serial communication channel following the defined protocol of communication (see Appendix 9.4).

This communication is made through a serial line running at 9600bps, 8 bit, no parity. Line level is 5V (TTL). The communication with the board is based on a request/answer protocol. The commands are identified by sets of 1 letter and two or more digits encoded with hexadecimal values. For each command, the board acknowledges by repeating the command itself and appending the answer. The full set of commands is reported in Appendix 9.4 with detailed explanation, syntax and example.

This custom protocol was developed for the specific use of the lmp 91000 AFE used with City Technology sensors. It can easily be adapted to fit any use by programming new commands or reprogramming existing one. The firmware is programmed using the Arduino variant of C++. The files can be downloaded on the website http://www.airsenseur.org/ or at the FTP site (sub directory AirSensEUR/Shields/Software/Firmware/ChemSensorBoard).

3.2.2 Java Front End

A Java interface was developed to select and setup the AFE parameters and the filter coefficients. This Front End can run both on a Windows or Mac computer. The communication can be done through an Arduino USB2SERIAL programmer or by mean of the custom USB2Serial acquisition board. In the case that the USB2SERIAL programmer is used for uploading parameters, the shield is directly powered by the programmer. Thus an external power supply for the chemical sensor board is not needed. The code source of the Java Front end can be downloaded at the FTP server under AirSensEUR/Shields/Software/JAVA Front End/ChemSensorPanel or at http://www.airsenseur.org/.

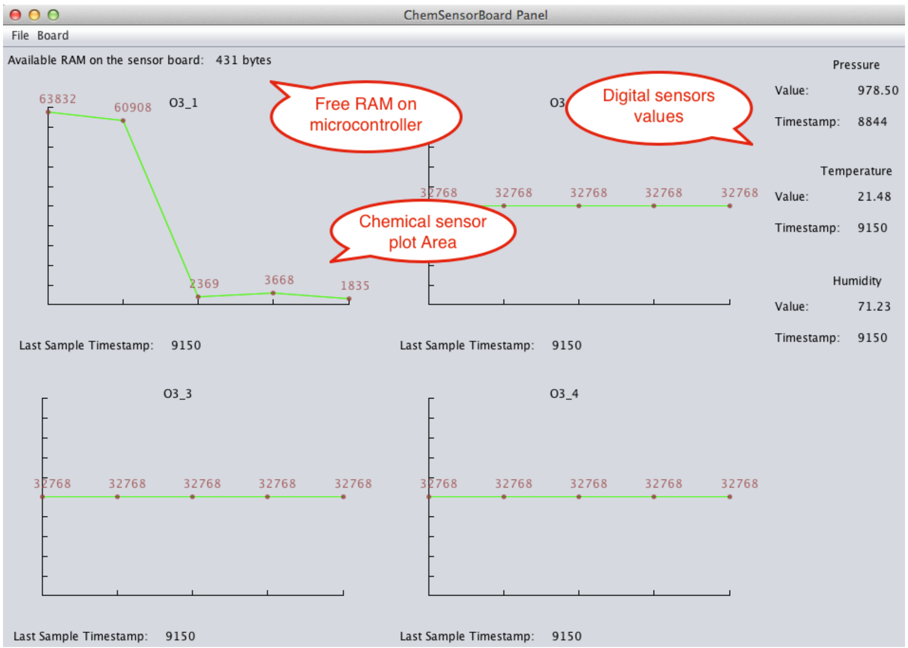


Figure 6: View of the Java Front End main panel

Figure 6 shows a view of the main panel of the Java interface. The main panel shows the available RAM of the ATMega328 on the top left corner. The responses of the ambient sensors are collocated on the right part. Finally the raw data coming from the gaseous sensor are displayed by four time-series plots on the panel. Each plot reports the last 10 samples together with the last valid timestamp for the associated sensor channel. The sensor responses correspond to the voltage output of the sensors that are digitally converted by the 16 bit ADC according to the range selected by sensor. For each sensor a set of 18 parameters can be tuned to acquire/improve the sensor response. The configuration panel can be divided in 3 part:

<u>Analog Front End parameters</u>

The first parameter to be set is the name of the sensor. It is a length limited custom string shown at the top of each plot panel. The name is associated to each chemical sensor and stored into the non-volatile memory.

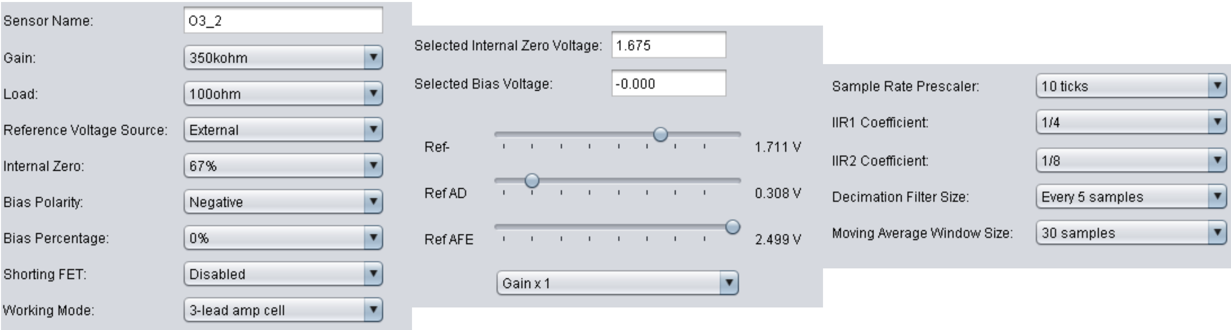


Figure 7: Sensor's configuration panel
(from left to right: AFE parameters, Reference voltage and Sampling parameters)

All the parameters needed to setup the Analog Front End in order to properly adapt it to a specific sensor model as shown on the left view of Figure 7. Each parameter is a one to one map with LMP91000 registers. Here is a list of all the parameters and the available configuration for each:

Gain: defines the transimpedance gain applied. It can be set to 8 values: **External**, **2.75 kOhm**, **3.5 kOhm**, **7 kOhm**, **14 kOhm**, **35 kOhm**, **120 kOhm** and **350 kOhm**. "External" corresponds to an external resistance of 1 MOhm. As this last possibility is independent form the AFE, accuracy is not guaranty so it is advised to use this option only for debug/testing.

Load: defines the load applied to the chemical sensor output lead. The load can be set on 4 resistance values: **10 Ohm**, **33 Ohm**, **50 Ohm** and **100 Ohm**.

Reference Voltage Source: correspond to the source of the analog reference voltage used by the AFE to generate bias and internal zero voltages. 2 choices are available: **Internal** and **External**. When Internal is selected, a fixed 5V is applied; when External is selected, the reference voltage needed by the AFE is generated by the external D/A converter.

Internal Zero: defines the ratio over reference source used by the AFE to generate the internal zero voltage. 4 set can be used: **20%**, **50%**, **67%** and **Bypass.**

Bias polarity: defines the polarity of the generated bias analog voltage which can be **Positive** or **Negative**.

Bias percentage: defines the ratio over reference source used by the AFE to generate the bias applied to the chemical sensor. This potential is usually set between the sensing electrode and the reference electrode. The bias percentage can be tuned between **0%** to **24%** by 2 % steps of Ref AFE (see below).

Shorting FET: the LMP91000 included a Field Effect Transistor (FET) which can be used to short cut the sensor when they are not powered. **Enabled**, **Disabled** turn respectively on and off this FET. An additional FET was mounted externally to the AFE to guaranty the functioning.

Working Mode: defines the working mode of the AFE between:

- *Deep Sleep:* the AFE is turned off. The sensor is not connected to the A/D converter. No power is drawn from the power supply.
- *2 leads ground ref:* the AFE is working in 2 leads ground referenced chemical sensors topology. This option is not supported by the 3 electrodes amperometric sensors.

- *Standby:* the AFE is partially turned off. The sensor is powered and biased but the transimpedance amplifier (Gain) is turned off.
- *3 leads amp cell:* defines the working mode used in this project with 3 electrodes amperometric sensors.
- *Temp (TIA ON):* the output of the AFE is connected to the embedded temperature sensor maintaining the transimpedance amplifier (Gain) on.
- *Temp (TIA OFF):* the output of the AFE is connected to the embedded temperature sensor but the transimpedance amplifier (Gain) is turned off for power saving.

For example, City Technology sensors already advices the value of bias potential, polarity, and load resistor for its sensors in a technical note [21]. Table 1 gather the information applied on the

Table 1: AFE configuration recommended by the manufacturer

Sensor name	Bias potential	Polarity	Load resistor
O3 3E1F	0	-	100 Ohm
NO 3E100	+200	+	100 Ohm
NO2 3E50	0	-	47 Ohm
CO 3E300	0	+	33 Ohm

AFE extracted from the manufacturer technical note for the selected sensors.

<u>*Reference voltage*</u>

This panel is dedicated to the setup of the different reference voltage applied to the sensor and the electronic. 4 parameters can be modified: *Ref-*, *Ref AD*, *Ref AFE* and *Gain*, (centre view Figure 7).

Ref-: defines the reference voltage applied to the A/D converter inverting input (Vin-).

Ref AD: defines the reference voltage applied to the A/D converter as Vad.

Ref AFE: defines the reference voltage applied to the Analog Front End. This option is active only when the Reference Voltage Source is set on External mode.

Gain: defines the range of the reference voltages generated by the onboard D/A converter. The range are define from 0 to 2.499V if x 1 is selected and from 0 to 5V for x 2.

The first two parameters (*Selected Internal Zero Voltage* and *Selected Bias Voltage*) are only read values which depend on the other parameters as explained below.

Selected Internal Zero Voltage: is calculated as a percentage of the Ref AFE defined in the Internal Zero of the Analog Front End parameters.

Selected Bias Voltage: is calculated as a percentage of the Ref AFE defined in the Bias percentage and affected by the Bias polarity of the Analog Front End parameters.

<u>*Sampling parameters*</u>

As already explained in the section 3.2.1, our custom firmware samples sensors values and performs a set of basic statistical operations on a periodical basis (right view Figure 7). Those sampling/filtering parameters are defined as below:

Sample Rate Prescaler: defines the main sample rate period for the A/D converter. It can vary from **1** to **100** and is expressed in ticks. 1 tick is equal to 10ms which means that the sample rate can vary from 100Hz down to 1Hz.

IIR1 Coefficient and **IIR2 Coefficient:** defines the denominator value for the coefficients of the Infinite Impulse Response filter [17] apply on the raw value. This kind of filter has been chosen for its efficiency and its small load of the internal RAM. Values available are: **Disabled**, **1/2**, **1/4**, **1/8**, **1/16**, **1/32**, **1/64**, **1/128**.

Decimation Filter Size: defines the decimation filter ratio from **Every 1 sample** to **Every 256 samples**.

Moving Average Window Size: defines the size of the moving average windows, from 0 to 60 samples.

3.3 Power consumption

A measurement of the power consumption of the AirSensEUR shield was done during laboratory's experiments. The shield was fully operational with 4 gaseous sensors form the City Technology Company and the daughter board (temperature, relative humidity and ambient pressure) with a sampling rate set as described in 4.4. The consumption did not overpassed 20mA with a 5V power supply equivalent to 0.100W

4 Assembling the AirSensEUR

4.1 Getting the PCB

Two types of PCBs are necessary:

1. The AirSensEUR sensor shield PCBs, which includes the sensor shield, the daughter board for temperature, humidity and pressure and the USB2Serial board schemes. It is possible to build your own PCBs from scratch using the BOM and the electronic schemes although the easiest way is to purchase them at LiberaIntentio[1].
2. An Arduino USB Serial Light Adapter that allow to upload the firmware to the AirSensEUR sensor shield [22]. It can be bought for example on Rs-online, Mouser or Digikey.

4.2 Installing the firmware

The firmware can be preinstalled on each sensor shield by the supplier, LiberaIntentio. However, if needed the firmware can be uploaded (see 4.2.1).

AirSensEUR is based on an ATMega328 microcontroller with Optiboot factory loaded. Optiboot [23] is a small program (called bootloader) that runs each time the microcontroller is reset or powered up. The bootloader waits some seconds for a specific set of commands coming from the serial line and, if found, enters in a "programming mode". This operating mode expects to receive a binary file through the serial line thus erasing and programming the internal flash. If, the specific set of commands were not found on the serial line, the bootloader starts the program (if any present) located to a fixed flash memory address.

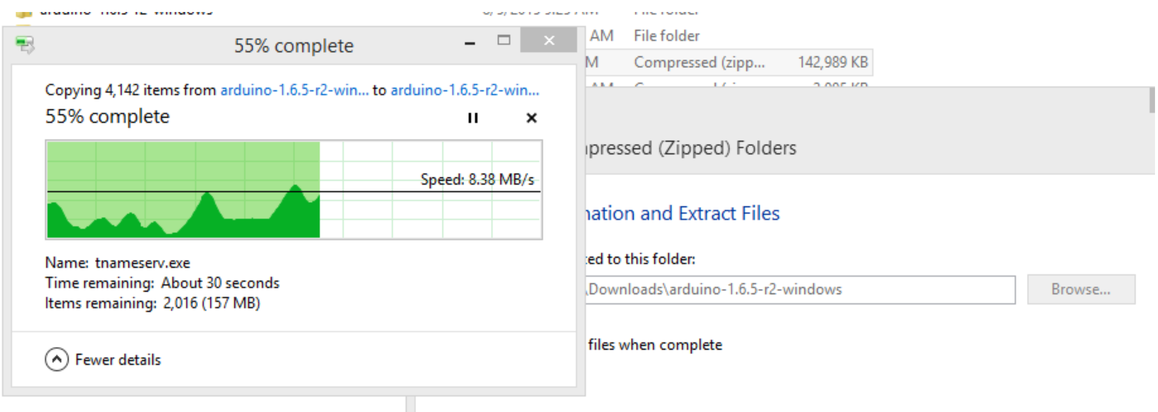
Optiboot can be found on each ATMega328 based board (for example the Arduino UNO™) and on the AirSensEUR board. For this reason, AirSensEUR is "seen" by the Arduino IDE like a "plain standard" Arduino UNO. Thus, AirSensEUR can benefit from a worldwide available open source code and libraries targeted to ATMega328 based Arduino™.

A custom firmware was developed to instruct the ATMega328 microcontroller to properly connect to other on-board peripherals on the AirSensEUR board, to generate the needed timings, read samples, pre-process them by filtering and temporarily store on the microcontroller memory. This firmware is also responsible for the implementation of a serial protocol used by an external host to setup working parameters and retrieve sampled data. This software is provided as source code and needs to be compiled then uploaded to the AirSensEUR for the very first time or if upgrade is needed. This operation can be done by following this step by step guide below.

4.2.1 Standard Operational Procedure, building and uploading the firmware

Step 1: Download and install the Arduino IDE

The Arduino™ IDE is available for Windows™ and Mac™ users. It can be downloaded from https://www.arduino.cc/ [24] (see print screen below). In this guide we refer to the 1.6.5 revision. We chose the .zip version because it does not require any administrative privileges on the target PC in order to be installed. The downloaded .zip package can be uncompressed in any folder.



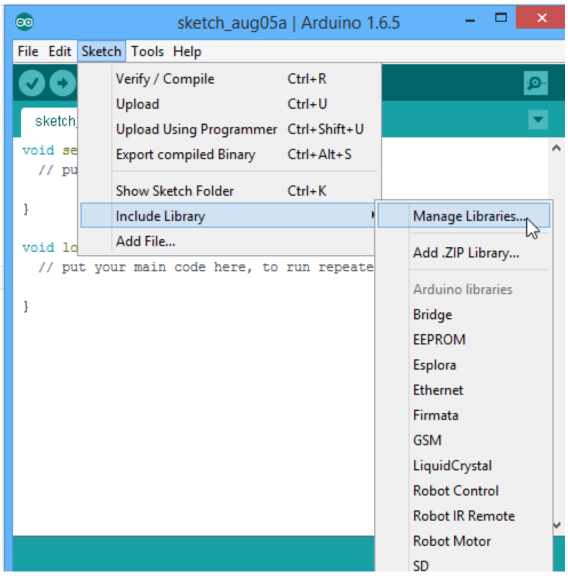
Step 2: Install external libraries

The AirSensEUR firmware requires two external libraries to be added. The first, "Timer One", helps for timing generation. The second, "MemoryFree", is used to retrieve the amount of volatile memory available for samples. The IDE helps the user to install those libraries through the menu option Sketch → Include Library

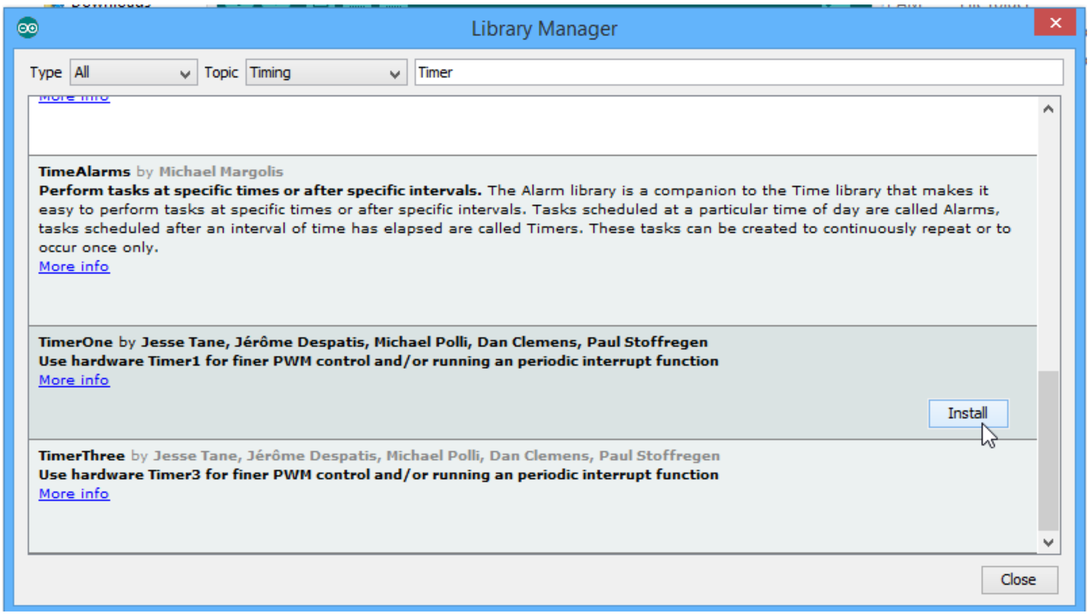
The timing library is already listed on the optional downloadable libraries. You can add it with a couple of clicks.

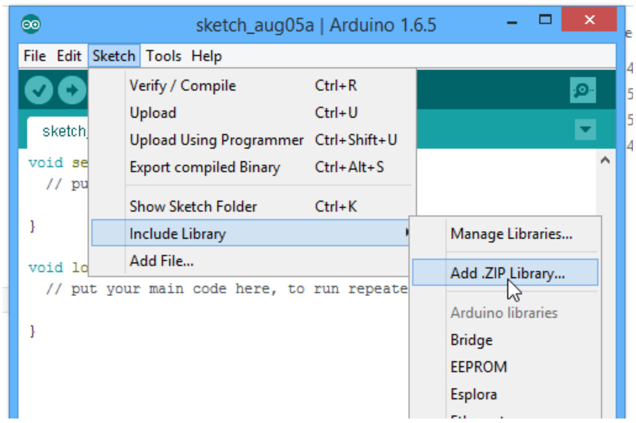
By clicking on the Sketch → Include Library → Manage Libraries, a Library Manager panel is proposed (see image on the right). Available libraries can be filtered out by changing the Type and Topic selectors and/or by typing a relevant keyword in the edit box.

Filter by "Timing" topic, then type "Timer" in the right edit box and you'll have a list with all timer related libraries available.



Select the “Timer One” library and click on the “Install” button (see image below). The library is now downloaded and installed on the IDE.



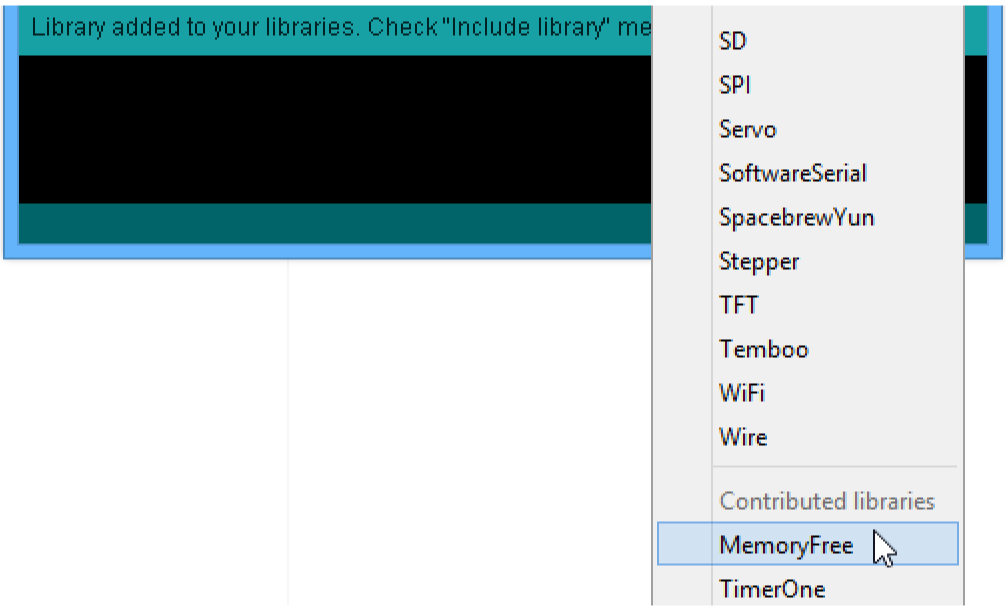


The second required library is not (yet) listed on the Library Manager panel and, for this reason, needs to be downloaded from github repository at https://github.com/mpflaga/Arduino-MemoryFree or at http://www.airsenseur.org/

Download the library as a .zip file and store on a temporary folder.

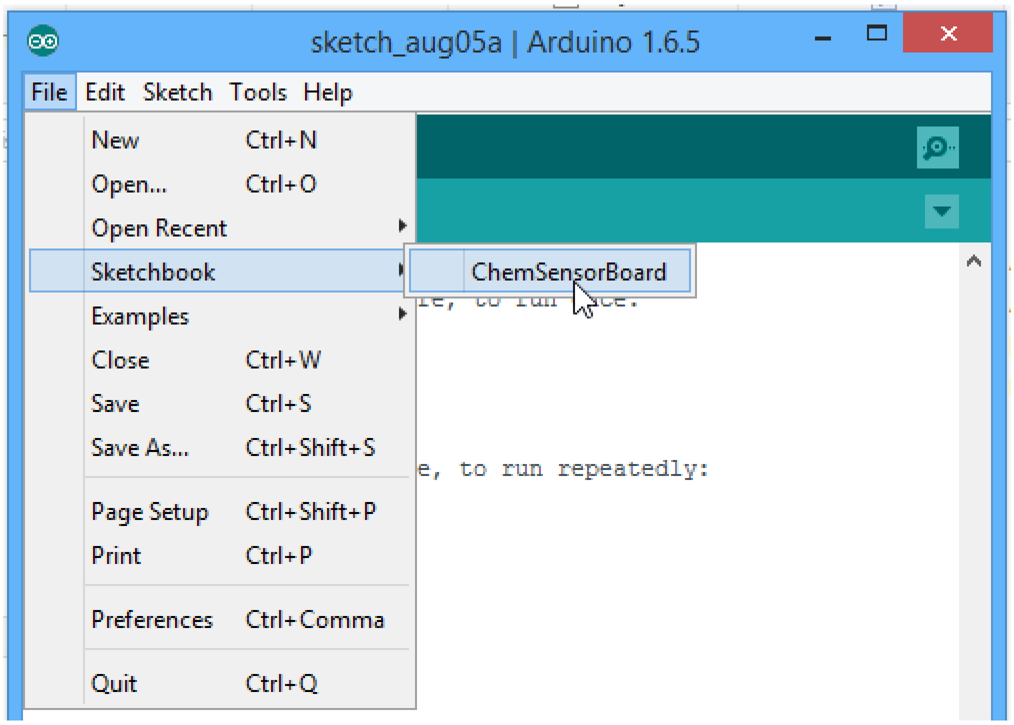
To add the MemoryFree library to the IDE, click on Sketch → Include Library → Add .ZIP Library then select the downloaded .zip file and confirm.

If all complete successfully, you should now have the two libraries listed on the bottom menu (Sketch → Include Library) as shown below.

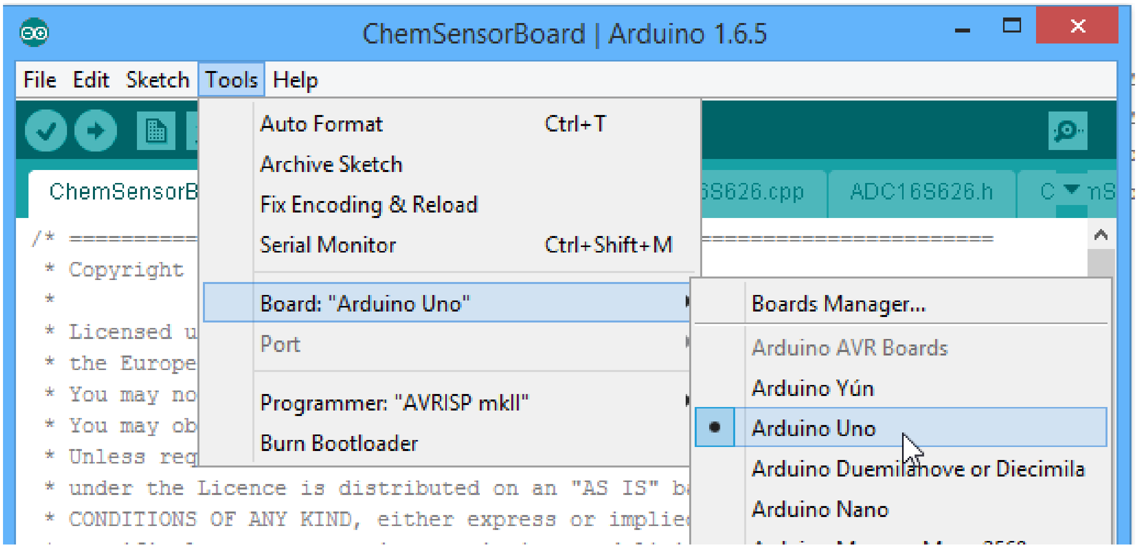


Step 3: Compile the AirSensEUR firmware

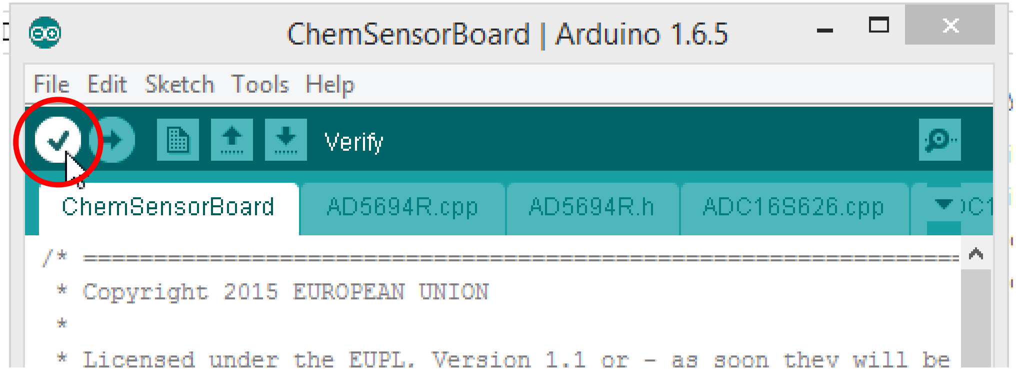
The software developed for Arduino ™ platform are called "Sketches". The IDE provides a favorite folder where all user Sketches can be stored ("Sketchbook"). This folder is usually named "Arduino" and is located on the user's Document folder. Copy the whole ChemSensorBoard folder in your sketchbook and restart your IDE in order to have it visible on the menu File → Sketchbook as shown below.



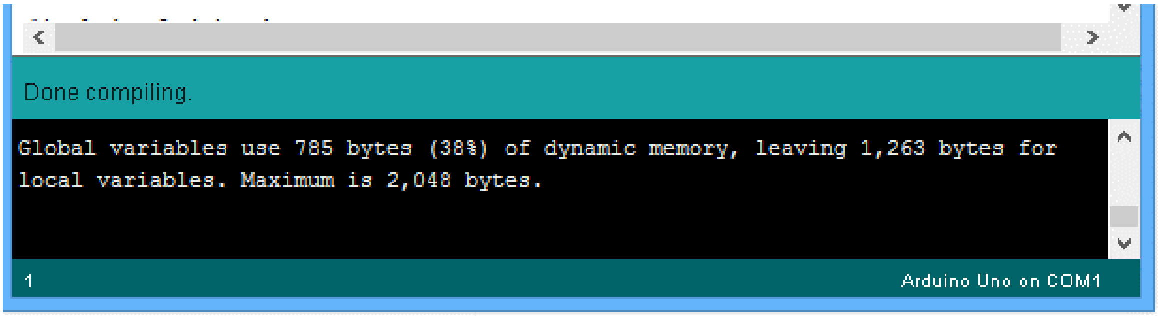
Click on Tools → Board → Arduino UNO to prepare the compiler for the AirSensEUR target.



Then click on the "Verify" pushbutton (it's the most left round button on the top bar, identified by a green flag mark) to start compiling the sketch for the AirSensEUR board.

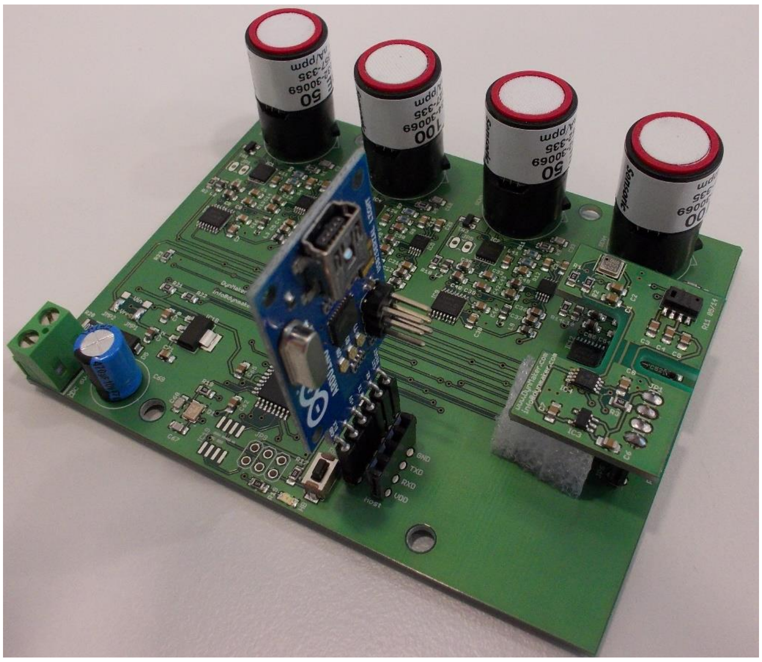


As soon as the compilation terminates, you should see a message as the one below in the IDE status panel.



Step 4: Upload the firmware to the AirSensEUR board

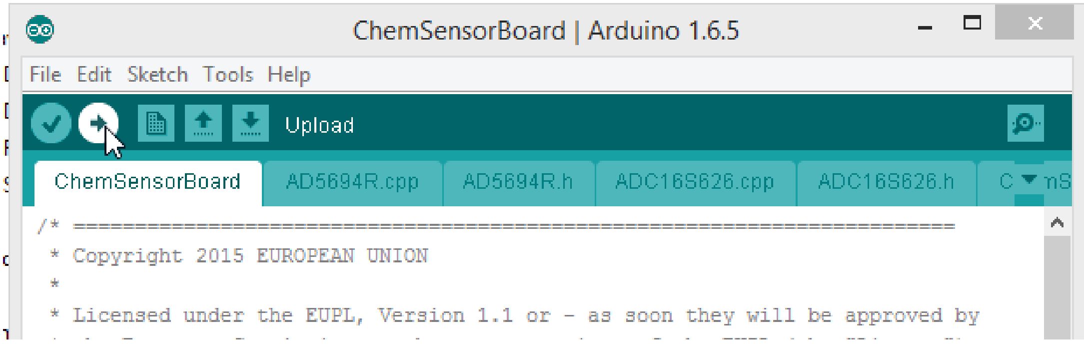
Connect your Arduino™ USB2Serial converter on the JP2 connector. The correct position is when the USB2Serial converter's component side is oriented to the Host connector on the AirSensEUR board (see right picture).



Connect the USB side to a USB port on your PC. Windows users need an .inf file to be installed for the Arduino™ USB2Serial converter; please follow the instructions that can be found at the product site webpage.

Wait until your system recognizes the Arduino USB2Serial converter.

Select the serial port where the USB2Serial is connected through the Tools → Port menu, then click on the Upload button located at the top bar.



The procedure takes some seconds and it's confirmed by a message on the bottom status panel. Congratulations. Your AirSensEUR board is ready to accept commands from the Java AirSensEUR Panel configuration program.

4.3 Selecting sensors and the parameter of the AFE of each sensor channel

The sensor shield is designed to acquire simultaneously data from 4 gaseous sensors, from the temperature/relative humidity sensor and from the pressure sensor. Based on the experiments carried out during the MACPoll project ([3-7]), we developed the shield to use the 3-electrode sensors from City Technology UK model Sensoric [12]. Initially, the City Technology sensors, diameter 16 mm, are mounted using a TO5 connector (see Appendix 9.2.2). However, the shield has been modified to accommodate other 2 or 3-electrodes sensor models by using different pin connection including:

- the sensors with 20 mm diameter, e. g. the 4 series of City Technology[25] or SGX Sensortech [26], the "miniature" series of Membrapor [27] and the A sensor series of Alphasense (Small sensor types A1, A3, AE, AF, AX, CE, CF and CX see [28])
- and the sensors with 32 mm diameter: e. g. the 7-series of City Technology or SGX Sensortech, the Membrapor "Compact" sensor series or the B sensor series of Alphasense .

Table 2 gives the type of sensors that can be used with each sensor channels. Figure 8 shows the dimension and position of each sensor on the shield.

Table 2: types of sensors that can be used with each sensor channels of the shield

Connector type	Sensor Description	Sensor 1 and 4	Sensor 2 and 3
Sensoric (TO5 plug)	3 electrodes sensors, connector with 4 pins	X	X
A/Miniature/4-Series sensor	2 or 3 electrodes sensors and up to 4 pins (diameter: 20 mm, pin diameter: 1.5 mm)	X	X
B/compact/7-Series sensor	2 or 3 electrodes and up to 4 pins (diameter: 32 mm, pin diameter: 1.0 mm)	X	

Appendix, 9.3 gives a list of the sensors manufactured by AlphaSense, City Technology and Membrapor that are likely to work with the AirSensEUR shield. In general, the sensitivity of the sensor decreases with their size: the 7-series are more sensitive than the 4-series that are in turn more sensitive than the City Technology sensors. However, other parameters of the sensor behaviour such as the drift over time, the cross sensitivities to other compounds, the effect of temperature and humidity are important as well.

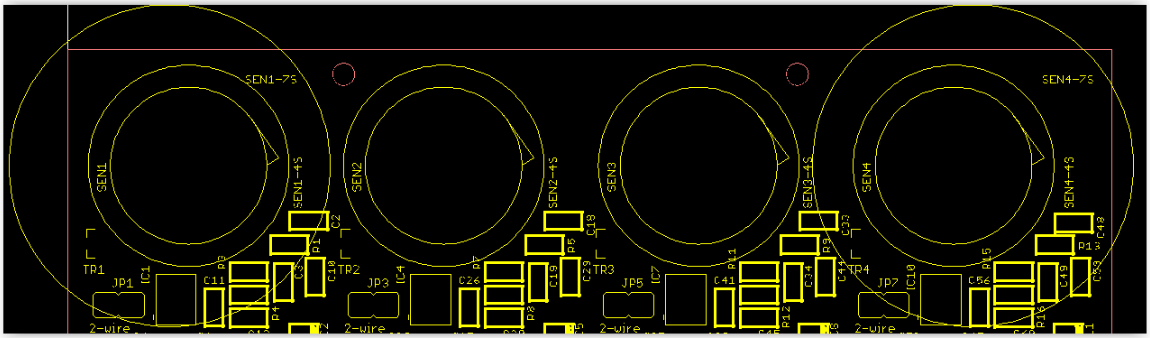


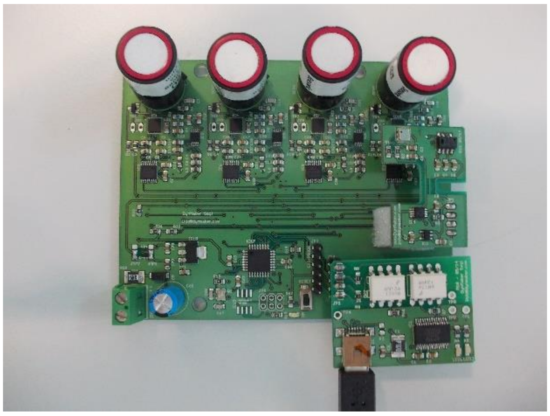
Figure 8: Types of sensors that can be used on the AirSensEUR sensor shield on the 4 channels

Currently we have only tested the City Technology models O3 3EIF, NO2 3E50, NO 3E100, CO 3E300 so that the sole information will be given for these sensors. However, some other brand and models show higher sensitivity for NO and would be worth testing.

Once sensors are selected, the pin connector for the 4-series or 7-series or the TO5 plug should be welded on the PCB. One can use, for example, the pin connectors presented in Appendix 9.2.2, choosing carefully the pin model fitted for the pin dimension of the selected sensors. Finally the sensor and the daughter board for auxiliary measurements can be plug on the PCB.

4.4 Setting the parameters of the sensors and the AFE of each channel with the JAVA front-end

The JAVA Front End is launched after connecting the sensor shield to your PC either through an Arduino USB2Serial converter (see below left picture) or with the AirSensEUR Serial2USB board (see below right picture). In the latter case an external power supply shall be connected to the sensor shield (at least 6 V).

The procedure is as follows:

- Be sure to install a correct Java Run-Time Environment for your Operating System (Java™ SE Runtime Environment 7 or higher)
- Launch the ChemSensorPanael.jar found in AirSensEUR/Shields/Software/JAVA Front End/Binary/ChemSensorPanel
- Click on the menu BOARD
- Choose CONNECT and select the Com port connected with the sensor shield and click on CONNECT. Success should be written at the bottom of the window when the connection has been established. Close the window.
- Click on the menu BOARD and select the sensor to setup
- When all the sensors are set up, click on the menu BOARD and click "Start sampling".
- In the main panel, the sensors responses are shown as described in Figure 6.
- Click on the menu BOARD and select "Stop sampling "to stop the data acquisition.

Table 3 gathers the parameters set up in one of the AirSensEUR shield during the evaluation experiments. These parameters are given as example and should be modified/tuned for each sensor mounted on the shield.

When starting the sampling process with the Java Front End, this one run a data acquisition session. This Java application logs all the data in a text file on the shield. For each sampling campaign (from start to stop), a csv formatted file is generated into the ChemSensoPanel folder. Each file is named respecting the following pattern:

Sample_DDMMYYYY_HHMM.txt

where DD, MM, YYYY, HH and MM are, respectively day, month, year, hours and minutes of the beginning of the campaign. Data are stored in consecutive lines according to the pattern: *C,SSSSS,TTTT*. In this string, *C* is an integer identifying the channel (0 to 3 for the chemical sensors, 4 for the pressure sensor, 5 for the temperature sensor and 6 for the humidity one), *SSSSSS* is the ASCII value of the sample and *TTTT* is the ASCII value of the associated timestamp.

Table 3: Experimental parameters chosen for the City Technology sensors presented in this report

	sensor 1 O3 3E1F	Sensor 2 NO 3E100	Sensor 3 NO2 3E50	Sensor 4 CO 3E300	Temperature	Humidity	Pressure
Gain	350 kOhm	350 kOhm	350 kOhm	350 kOhm	N/A	N/A	N/A
Load	100 Ohm	100 Ohm	100 Ohm	33 Ohm	N/A	N/A	N/A
Reference Voltage source	External	External	External	External	N/A	N/A	N/A
Internal Zero	67 %	67 %	67 %	67 %	N/A	N/A	N/A
Bias Polarity	Negative	Positive	Negative	Positive	N/A	N/A	N/A
Bias Percentage	0 %	10 %	0 %	0 %	N/A	N/A	N/A
Shorting FET	Disabled	Disabled	Disabled	Disabled	N/A	N/A	N/A
Working Mode	3-lead amp cell	3-lead amp cell	3-lead amp cell	3-lead amp cell	N/A	N/A	N/A
Ref -	1.674 V	1.342 V	1.674 V	1.699 V	N/A	N/A	N/A
Ref AD	±0.5 V	±0.5 V	±0.5 V	±0.5 V	N/A	N/A	N/A
Ref AFE	2.499 V	2.007 V	2.499 V	2.499 V	N/A	N/A	N/A
Gain	x 1	x 1	x 1	x 1	N/A	N/A	N/A
Sample Rate Prescaler	10 ticks	10 ticks	10 ticks	10 ticks	10 ticks	10 ticks	25 ticks
IIR1 Coefficient	1/4	1/4	1/4	1/4	1/4	1/4	1/4
IIR2 Coefficient	1/8	1/8	1/8	1/8	1/8	1/8	1/8
Decimation	Every 5 samples	Every 5 samples	Every 5 samples	Every 5 samples	Every 5 samples	Every 5 samples	Every 5 samples
Moving Average Window Size	30 samples	30 samples	30 samples	30 samples	30 samples	30 samples	30 samples

To use other sensors, the procedure given in the following figure may be applied to estimate the parameters of the configuration of the sensor channels. This allows estimated the optimal parameters from a data acquisition point of view. However, Ref- is likely affecting the chemical reaction according to the electrode metals, type of sensor electrolyte and dimensions of the cell. It seems that information about the best value for Ref- is not fully available. Thus it should be estimated experimentally by users keeping in mind that when optimizing ref-, interactions ref- and the oxido-reduction reaction will take place.

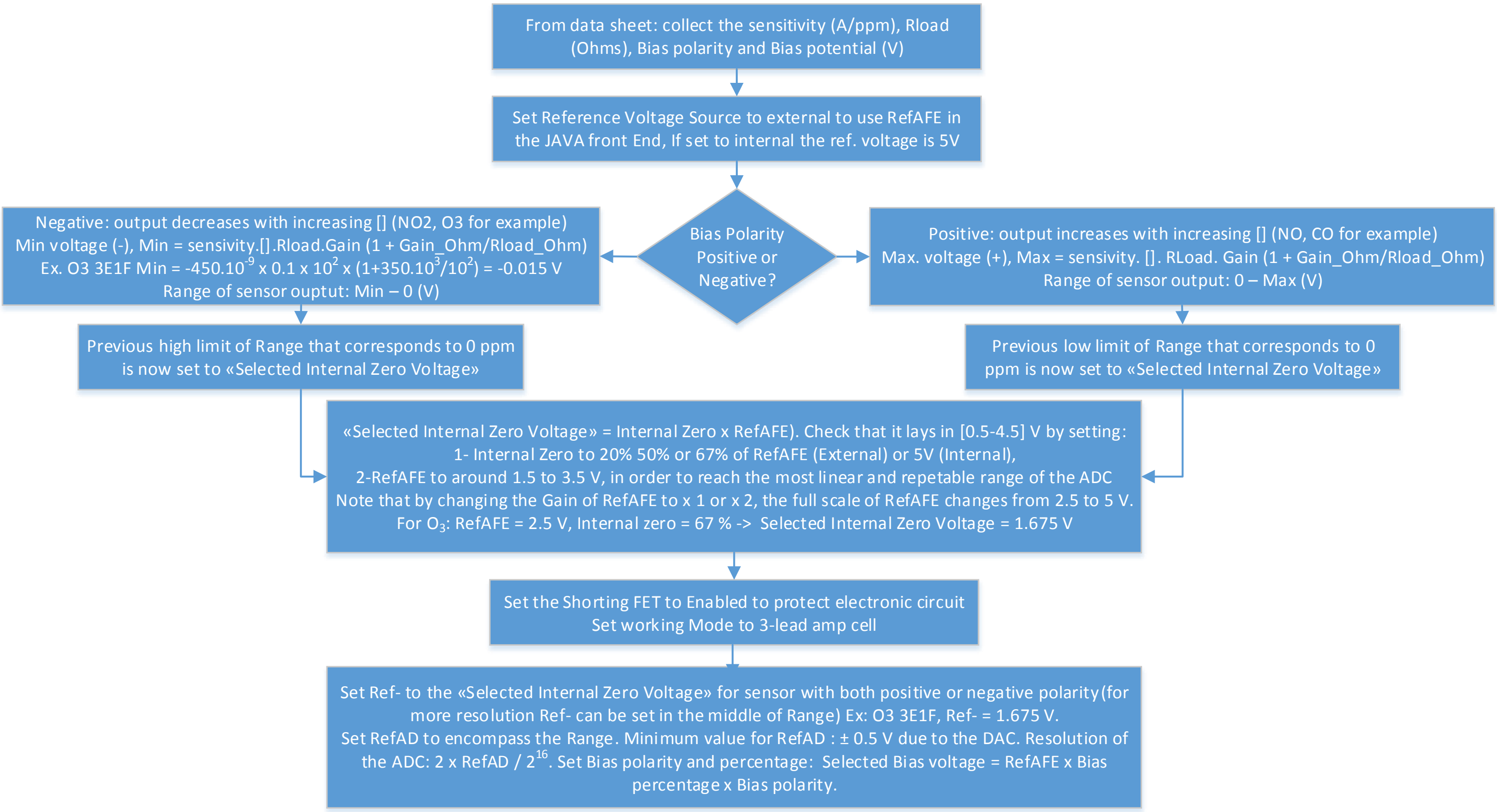


Figure 9: Procedure to follow to estimate the parameters of the configuration of the chemical sensors

5 Evaluation of sensor performances

5.1 Exposure chamber for laboratory tests

The gas sensors were evaluated in our in-house exposure chamber. This chamber allows the control of gaseous interfering compounds, temperature, relative humidity and wind velocity (Figure 10). The exposure chamber is an "O"-shaped ring-tube system, covered with dark insulation material. The exposure chamber can accommodate the micro-sensors directly inside the "O"-shaped ring-tube system.

A Labview software was developed for controlling the exposure chamber and for easy programming of a set of experiments under different controlled conditions: temperature, humidity, wind velocity, gas compounds (ozone O_3, nitrogen monoxide NO, nitrogen dioxide NO_2 and carbon monoxide CO), and other gaseous interfering compounds. It allowed setting criteria for the stability of each parameter and for duration of each step. The software is also able to manage data acquisition. All results (exposure conditions and sensors responses) are collected in Access databases for latter data treatment. The data acquisition system had a frequency of acquisition of 100 Hz and average over one minute when stored. During experiments, an automatic system (PID feed-back loop) used the reference measurements of gaseous compounds, temperature, humidity and wind speed to auto-correct the gas mixture generation system, temperature controlling cryostat and wind velocity to reach the target conditions.

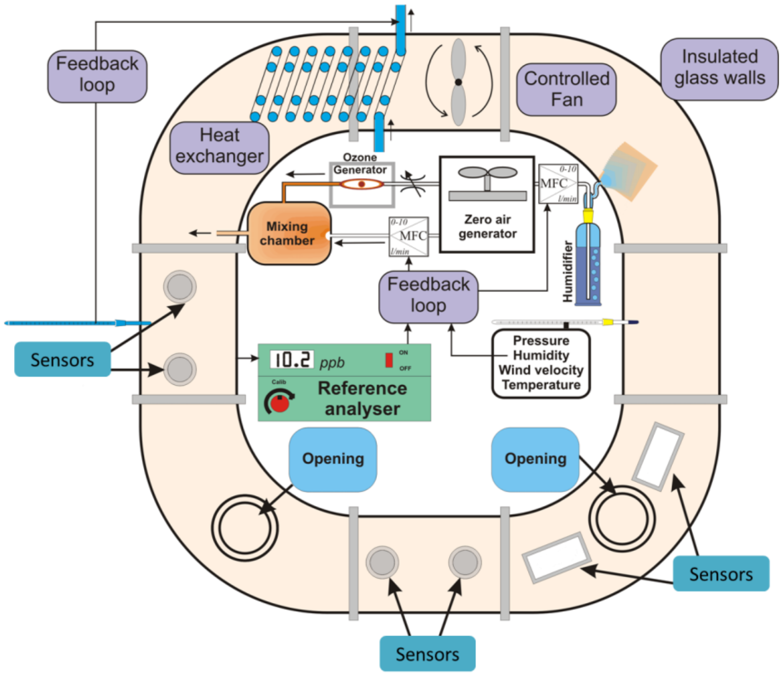


Figure 10: Exposure chamber for micro-sensors used in laboratory

5.2 Gas mixture generation system

For generating O_3, two MicroCal 5000 Umwelttechnik MCZ Gmbh (G) generators were used. These generators are equipped with UV lamps placed in thermos-insulted chamber whose UV beam is controlled by a regulated current intensity.

CO, SO_2 and NOx mixtures were directly generated by dynamic dilution from highly concentrated cylinders from Air Liquide. NH_3 and also NO_2 were generated with an in-house designed permeation system, using permeation tubes from Dynacal and Calibrage that were weighed every 3 weeks.

5.3 Reference measurements of gaseous compounds in the exposure chamber

O_3 was monitored using a Thermo Environment Model 49C UV-photometer. The analyzer was calibrated before the experiments using an O_3 primary standard. It consists of a TEI Model 49 C Primary Standard, Thermo Environmental Instruments cross-checked against a long-path UV photometer (National Institute of Standards and Technology, reference photometer n° 42, USA). NO/NOx/NO_2 were measured using a Thermo Environment Model 42i TL chemiluminescence analyzer, calibrated against a permeation system for NO_2 and a NO working standard consisting of a gas cylinder at low concentration (down to 50 ppb) certified against a Primary Reference Material of the Dutch Measurement Institute (NMI VSL – NL). SO_2 was measured using an Environment SA AF 21 M, calibrated with a working standard consisting of gas cylinder at low concentration (down to 50 ppb) certified against a Primary Reference Material of NMI VSL - NL. The calibration of the analyzer was confirmed by cross-checking with the permeation method. CO was measured using a Thermo Environment Model 48i-TLE NDIR analyzer, calibrated with a CO working standard consisting of a gas cylinder at low concentration (down to 1 ppm) certified against a Primary Reference Material of NMI VSL - NL. For interference testing, NH_3 concentration was estimated based on the dilution parameters. Finally CO_2 measurements were done using a differential non dispersive Infrared gas analyzer Li-cor 6262, calibrated with a CO_2 cylinder (369 ppm for Air Liquide) and zero air obtained from an ultra-pure Nitrogen cylinder. The sampling line of each gas analyzer was equipped with a Naflyon dryer to avoid interference from water vapor on O_3, NOx, SO_2 and CO analyzer.

In addition, some other parameters were recorded and/or controlled such as temperature, relative humidity, wind velocity and pressure. Two KZC 2/5 sensors from TERSID (one with ISO 17025 certificate) were used to monitor both temperature and relative humidity. One sensor was used to monitor in real-time using our in house LabView software, the second one was used to register these parameters. The temperature of the exposure chamber was regulated using 3 refrigerated/heating circulators. One cryostat (Julabo (G) Model SP-FP50) was used to control the temperature inside the exposure chamber, another one (Julabo (G) Model HE-FP50) for the surface of the O-shaped glass tube and the last one (Julabo (G) Model HE-FP50) was devoted to the control of temperature of the humid and dry air flows. These cryostats used a laboratory calibrated pt-100 probe placed inside the exposure chamber. One wind velocity probes based on hot-wire technology was used to monitor wind velocity. One pressure gauge DPI 261 from Druck (G) was used to monitor pressure inside the exposure chamber. A fan ventilator was placed in the chamber to control wind velocity through the LabView software control, Papst (G) model, DV6224, 540 m^3/hr.

To assure the quality control of the reference measurements, during the experiments, the O_3 analyzer was monthly checked using a portable O_3 generator SYCOS KTO 3 (Ansyco, GmbH - G) certified against the laboratory primary standard (UV photometer NIST n°42). The NO_2, SO_2 and CO analyzers were calibrated once a month using cylinders certified by the ERLAP laboratory. ERLAP is ISO-17025 accredited (ACCREDIA-IT, n°1362) for the measurement of O_3, NO_2, SO_2 and CO according to EN 14625:2012, EN 14211:2012, EN 14212:2012 and EN 14626:2012, respectively. Several tests were performed to confirm the homogeneity of exposure conditions in the chamber at several positions in the exposure chamber.

6 Results

All the results are given for new sensors after a few days of warming in the chamber. In some case, it has been observed that the results of these evaluation may change, for example the effect of humidity on O_3 sensors is no more linear after 6 months of use of the sensor.

6.1 Response time

The response time experiments were carried out during the MACPoll project but only for the NO2 3E50 and O3 3E1F sensors, which will be presented in this paragraph. The response time of sensors, t_{90}, was computed by estimating $t_{0\text{-}90}$ and $t_{90\text{-}0}$, the time needed by the sensor to reach 90 % of the final stable value, after a sharp change of test gas level from 0 to 80 % of the full scale (FS) (rise time) and from 80 % of FS to 0 (fall time). Four determinations of rise and fall time were performed. The averaging time of the analyser was set to 20 seconds in order to get a fast response. For this experiment, the controlled conditions in the exposure chamber shall be established after a few minutes. Seen the internal volume of the exposure chamber (about 120 L), it was decided to use the automatic bench that ERLAP uses for the European inter-comparison exercises of the National Reference Laboratories of Air Pollution [29] that can generated mixture with a flow of about 100 L/min.

Table 4: Response time of NO2 3E50 and O3 3E1F sensors

Sensors	Full scale	t_{90}	$t_{0\text{-}90}$	$t_{90\text{-}0}$
NO2 3E50	100 ppb	98 s	128 s	68 s
O3-3E1F	90 ppb	60 s	90 s	30 s

Given that any change of an influencing variable would result in overestimating t_{90}, temperature, humidity and the interfering gas compounds (e. g. NO_2 when testing O_3) were kept constant with Relative Standard Deviations (RSD) of within 1% at FS. For this experiment, the controlled conditions in the exposure chamber shall be established after a few minutes. Seen the internal volume of the exposure chamber (about 120 L), it was decided to use the automatic bench that our laboratory, European Reference Laboratory for Air Pollution (ERLAP-JRC-IES) uses for the European inter-comparison exercises of the National Reference Laboratories of Air Pollution (Barbiere et al., 2011) that can generated mixture with a flow of about 100 L/min.

Table 4 shows the t_{90} with the stabilization time of the exposure chamber and the response times of the analyser being subtracted. Sensors in themselves are rather fast as they reach the stability after less than 2 minutes.

6.2 Calibration

To check the conversion of the sensor responses into gas concentration units, a calibration of each sensors against its target gas was performed. Levels of pollutant were selected to correspond to the air pollution levels expected in ambient air. Figure 11 shows the calibration plot based on a 45 minutes average with the standard deviations of the 45 values as error bars. Temperature and relative humidity were kept under control during the experiment, respectively 22°C and 60 %.

Using linear models for NO, NO_2 and CO sensors, the standard deviation of the residuals was found equal to 4.7, 2.1 ppb and 0.01 ppm respectively. For O_3, a quadratic model was applied to slightly decrease the residuals to the reference values. It results in a standard deviation of the residuals smaller than 0.9 ppb for the O3 3E1F.

6.3 Limit of detections

The limit of detection of the sensor was calculated using the standard deviation of sensor values for 45 consecutive minute measurements at 0 ppb and 80 % of full scale. All parameters suspected to have an effect on the sensor response (target gas, gaseous interfering compounds, temperature and humidity) were kept under control with RSD lower than 1 %. The limits of detection (see Table 5) were estimated as 3s where s is the standard deviation of repeatability for the 0-ppb level.

Each sensor was calibrated independently, in the range of concentration levels expected in ambient air. The limit of detection of the O_3 sensor is well adapted to the level of ambient air pollution. For the NO_2 and NO sensors, whose sensitivities are lower, the averaging time must be increased to reach acceptable levels, an hourly average allowing a limit of detection about 2.2 and 9.7 ppb respectively.

Table 5: Limit of detection of sensors, minute values

Sensors	O3 3EIF	NO2 3E50	NO 3E100	CO 3E300
Sensitivity, nA/ppm	471 (RL = 100 Ω)	215 (RL = 47 Ω)	44 (RL = 100 Ω)	83 (RL = 33 Ω)
Shield output signal, mV	14.5 @ 100 ppb	5.0 @ 100 ppb	7.6 @ 100 ppb	23 @ 1 ppm
Limit of detection	3.2 ppb.min	16.7 ppb.min	74.9 ppb.min	0.056 ppm.min

6.4 Short and long term drifts

Short and long term drift experiments were carried out during the MACPoll project. They were performed on sensors mounted on evaluation board from the City Technology-UK [25]. Here below, the evaluations for the O3 3E1F and NO2 3E50 sensors are presented. Further laboratory testing should be performed in order to evaluate the short and long-term drifts for the CO and NO sensors.

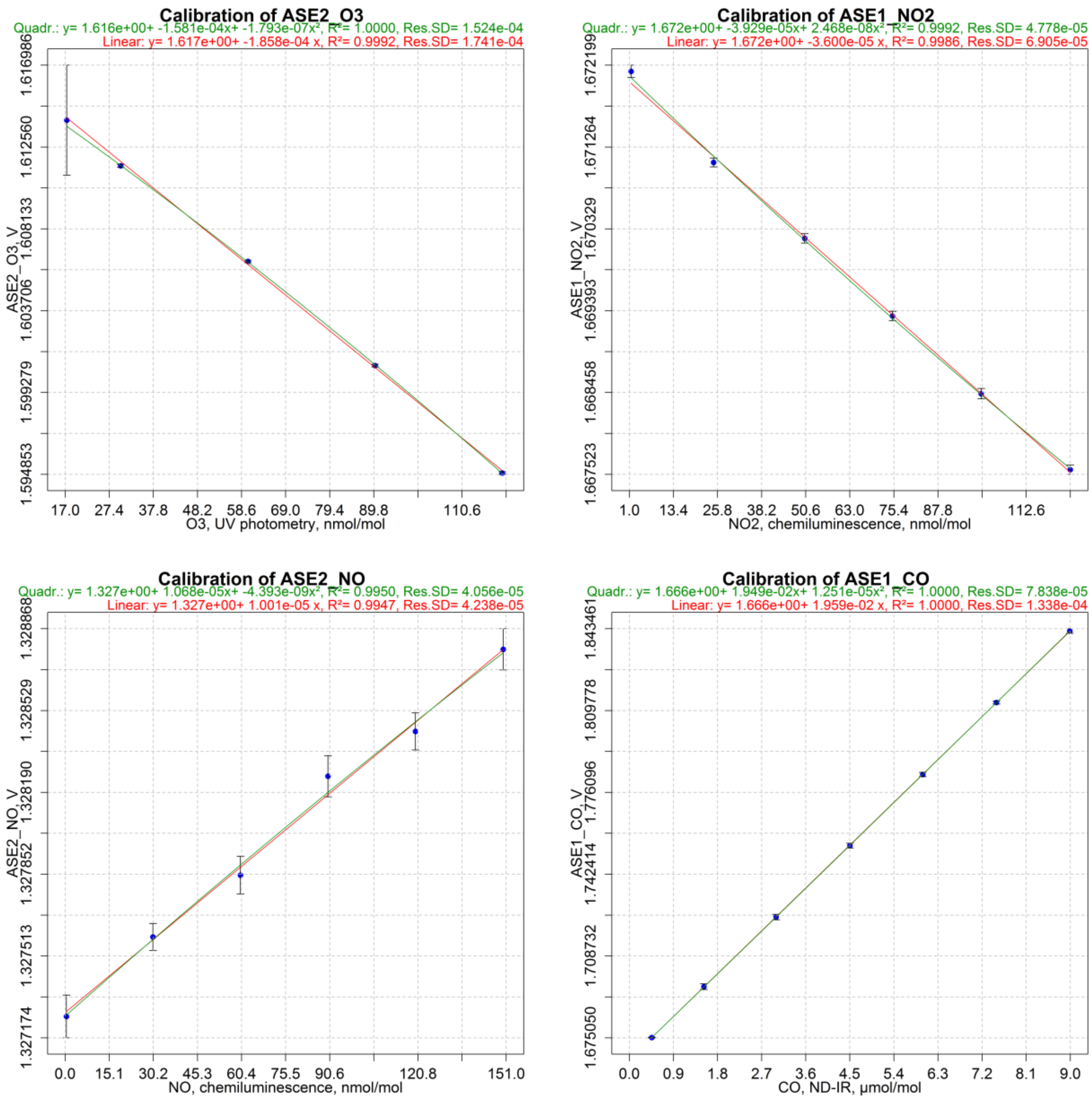


Figure 11: Calibration of O_3, NO_2, NO and CO City Technology sensors mounted on the AirSensEUR shield.

6.4.1 Short term drift

A few hourly measurements were carried out on several consecutive days at 0 ppb, 50 % and 80 % of the FS scale of the sensor when stable temperature, humidity and interfering gaseous compounds conditions were reached. The short term stability was estimated using (1) where R_s are the calibrated sensor responses at 50 % and 80 % of the FS at t_0 ($R_{s,before}$) and 24 hours later ($R_{s,after}$); N is the number of pairs of measurements. Figure 12 shows that the maximum drifts were up to 1.9 and 2.6 ppb for O_3 and NO_2 sensors, respectively.

$$\boldsymbol{D_{ss}} = \frac{\sum_{1}^{N9}|\boldsymbol{R_{s,after}} - \boldsymbol{R_{s,before}}|}{\boldsymbol{N}} \qquad \text{Equation 4}$$

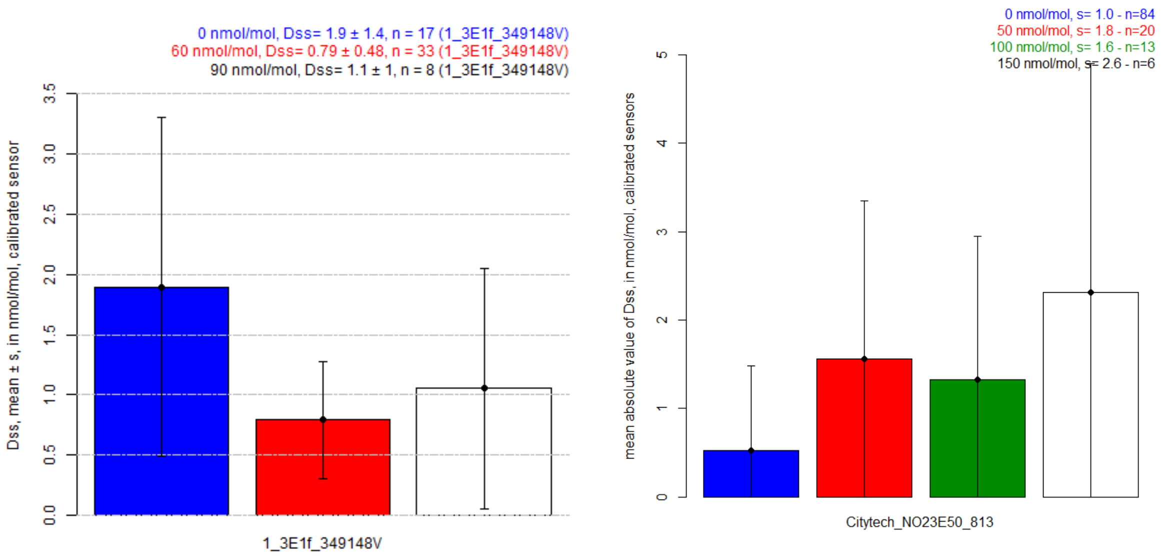


Figure 12: Short term stability for the O3 3E1F (left) and NO2 3E50 (right) sensors.

6.4.2 Long term drift

For the long term drift, as for the short term drift, the study was carried out measuring sensor response at 0, 60and 90 ppb for O_3 and 0, 50, 100 and 150 ppb for NO_2. The long term drift stability was estimated using the trends of the sensor responses from the beginning to the end of all laboratory experiment. As for the short term drift experiments, temperature, humidity and gaseous conditions were kept under control (less than 0.4 °C and 0.4 %) in order to avoid that their scattering may interfere with the sensor variability. Figure 13 shows that both the O3 3E1F and the NO2 3E50 sensors suffer from a significant drift over a long period of time (150 days for O_3 experiments and 250 days for NO_2). O3 3E1F shows an increasing drift whereas NO2 3E50 shows a decreasing trend. For each sensor type the slope of the drift changes linearly with the test level.

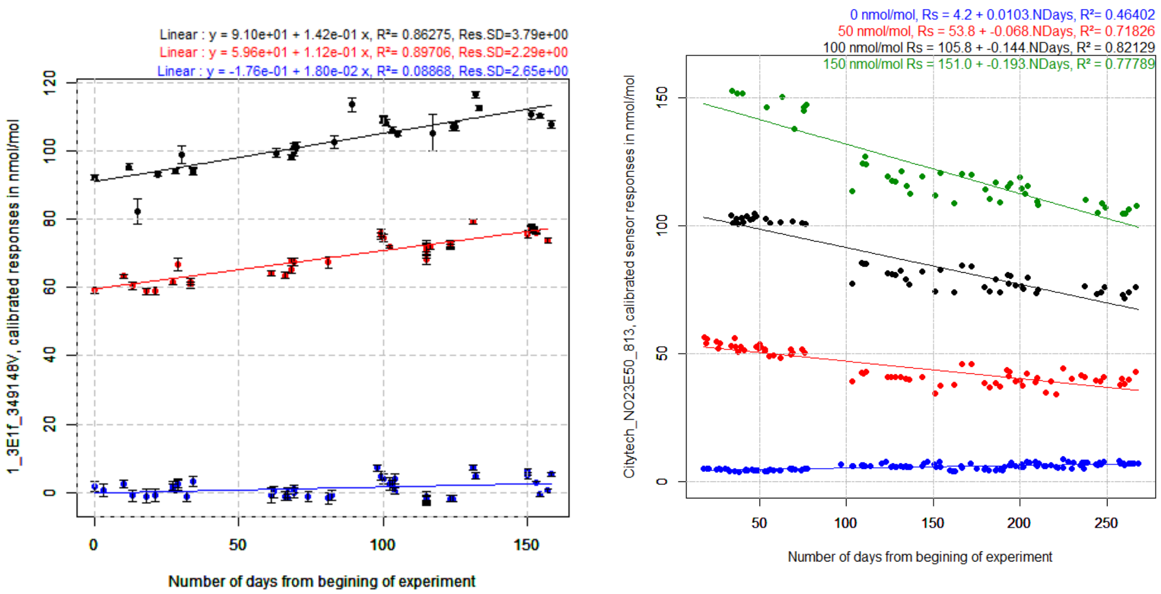


Figure 13: Long term stability for the O3 3E1F (left) and NO2 3E50 (right) sensors.

6.5 Gaseous interfering compounds

Electrochemical sensors generally suffer from cross sensitivity to other gaseous species. O_3, NO_2, NO, CO and SO_2 were selected for interference testing and they were set at the levels expected in ambient air at background and traffic sites. The influence of each compound on the sensors was determined once at a time in absence of other compounds. The levels of interfering compounds were set at the same level as the ones of the calibration experiment (see Figure 11) at the same temperature (22°C) and relative humidity (60 %) conditions. The sensors were exposed for one hour after reaching stability and then three independent measurements were performed. All gaseous compounds (apart from NH_3 for which we relied on gravimetric values) were measured using reference methods of measurement with a low expanded uncertainty of measurements (less than 5 %) traceable to (inter)nationally accepted standards (see 5.3). The sensitivity coefficients of the sensors to all tested gaseous interfering compounds are given in Table 6.

Table 6: Results of interference testing, the sensitivity coefficients give the response of the sensors in ppb per ppb of gaseous interfering compound, excepted for CO which is in ppm

Sensors	Interfering compounds	Sensitivity coefficients	Sensors	Interfering compounds	Sensitivity coefficients
O3-3E1F	NO_2	0.53 ± 0.026, ppb/ppb	NO2-3E50	O_3	1.53 ± 0.015, ppb/ppb
	NO	-0.018±0.0030, ppb/ppb		NO	-32 ±3.2, ppt/ppb
	CO	-0.11 ± 0.035, ppb/ppm		CO	-1.22 ± 0.050, ppb/ppm
	SO_2	-0.10 ± 0.017, ppb/ppb		SO_2	-2.48 ± 0.049, ppb/ppb
NO-3E100	O_3	-0.16 ± 0.033, ppb/ppb	CO-3E300	O_3	-0.74 ± 0.54, ppb/ppb
	NO_2	0.23 ± 0.031, ppb/ppb		NO_2	-7 ± 111, ppt/ppb
	CO	2.2 ± 0.23, ppb/ppm		NO	0.50 ± 0.080, ppb/ppb
	SO_2	0.52 ± 0.86, ppb/ppb		SO_2	-3.1 ± 5.3, ppt/ppb

Note: The effect of the long term drift on sensor was not corrected since it still had to be fully estimated. Thus the sensitivity coefficients may be slightly incorrect (see 6.4.2).

The sensitivity coefficients are calculated as the slope of the linear relationships between the calibrated sensor responses and the interfering compounds. Taking into account the typical abundance of pollutants in ambient air and the sensitivity coefficients of Table 6, one can observe that NO_2 for O_3 sensor and SO_2/O_3 for NO_2 sensor are the major interfering compounds. For the NO sensor, the sensitivity coefficients are significant O_3, NO_2 and CO. The CO sensor show the lowest cross-sensitivities, likely because the levels of compounds are in the ppb range while the sensor measures hundreds of ppb of CO. O_3 and NO are slightly significant for the CO sensor.

6.6 Meteorological and physical parameters

6.6.1 Temperature and Relative Humidity

Sensor's responses can also be influenced by changes of temperature or relative humidity. To evaluate these effects, two series of tests were carried out including temperature and humidity cycles while the main gas were kept constant. The range of relative humidity spread between 40% to 80% with 10% step in a hysteresis cycle with a 1st rise then 1 fall and finally a 2nd rise of RH%). The same experimental setup was used for temperature. The range of temperature changed between 7 and 37 ºC by step of 5 ºC (see Figure 14). The sensitivity coefficients of the O_3, NO_2, NO and CO sensors are given in Table 7 with O_3 and NO_2 scatter plots in Figure 14. The O_3 and NO_2 sensors highly suffered from changes of temperature and humidity. The CO sensor appears to be unaffected by change in humidity or temperature while NO suffered a huge dependence on temperature and a small one on humidity.

Table 7: Evaluation of temperature and humidity effect, the sensitivity coefficients give the sensor responses in ppb, per Celsius degree and percentage of relative humidity

Sensors	Influencing variables	Sensitivity coefficients	Sensors	Influencing variables	Sensitivity coefficients
O3-3E1F	Temperature	6.6 ± 0.090, ppb/°C	NO2-3E50	Temperature	26.8±0.30, ppb/°C
	Humidity	0.058 ± 0.055, ppb/%		Humidity	0.56 ± 0.043, ppb/%
NO 3E100	Temperature	-53.4 ± 0.76, ppb/°C	CO 3E300	Temperature	-25.6 ±1.4, ppb/°C
	Humidity	-0.17 ± 0.052, ppb/%		Humidity	0.26 ± 0.82, ppb/%

Note: The effect of the long term drift on sensor was not corrected since it still had to be fully estimated. Thus the sensitivity coefficients may be slightly incorrect (see 6.4.2).

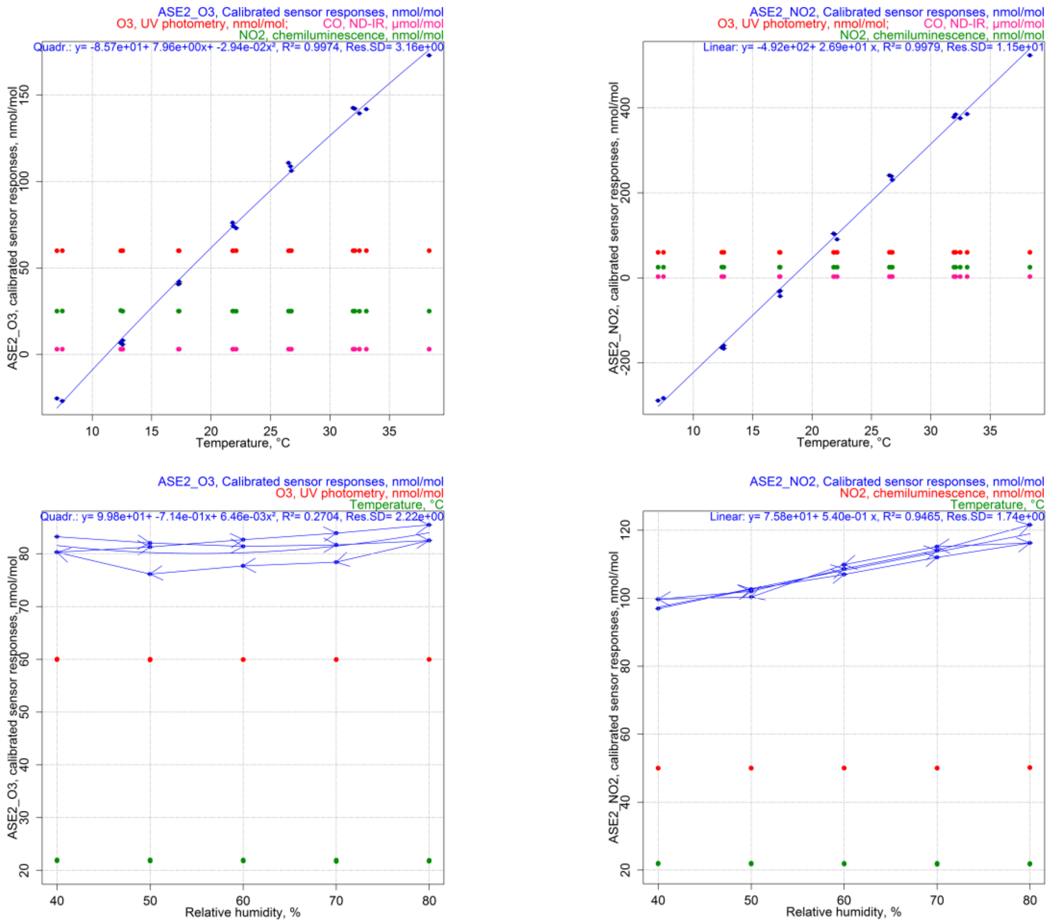


Figure 14: Example of temperature effect (upper row) at constant humidity level, and humidity effect (lower row) at constant temperature for the ozone (left column) and NO2 (right column) on sensors

6.6.2 Hysteresis

Hysteresis is a shortcoming of a sensor when its response depends both on the current state of the sensors and also on its past environment. During the MACPoll project, we evaluated the dependence of sensors when exposed to the same levels of pollutants with a different trend. The estimation of the dependence of sensors toward hysteresis was carried out by testing a ramp of rising concentration of O_3 or NO_2 levels, followed with a ramp of decreasing level and finally with a rising ramp. Both for O_3 and NO_2, almost no hysteresis effect could be observed (see Figure 15).

6.6.3 Final considerations

The City Technology O_3 and NO_2 sensors were also tested within the MACPoll project, using the City Technology evaluation board in place of the AirSensEUR shield. The estimated sensitivity coefficients are given in Table 8 [31]. While the sensitivity coefficients for interfering compounds are similar in both studies, huge differences can be observed for temperature and humidity. They were found much lower in Table 8. It is likely that the discrepancies come from the values of Ref-, bias potential, Ref AD, Ref AFE and Gain that are given in Table 3 and that these values may need further optimization.

Table 8: Gaseous interfering compounds: sensitivity coefficients (ppb/ppb or ppb/ppm for CO). For temperature and humidity: sensitivity coefficients (ppb/°C or ppb/%).

Sensors	O_3/ NO_2	NO	CO	CO_2	NH_3	Temperature	Humidity
O3 3E1F	0.76 (NO_2)	-0.011	$7.0\ 10^{-5}$	$3.5\ 10^{-3}$	$1.6\ 10^{-3}$	1.3	-0.022
NO2 3E50	1.5 (O3)	-0.058	-1.6 10-3	-1.3 10-2	-1.1 10-1	0.16	0.062

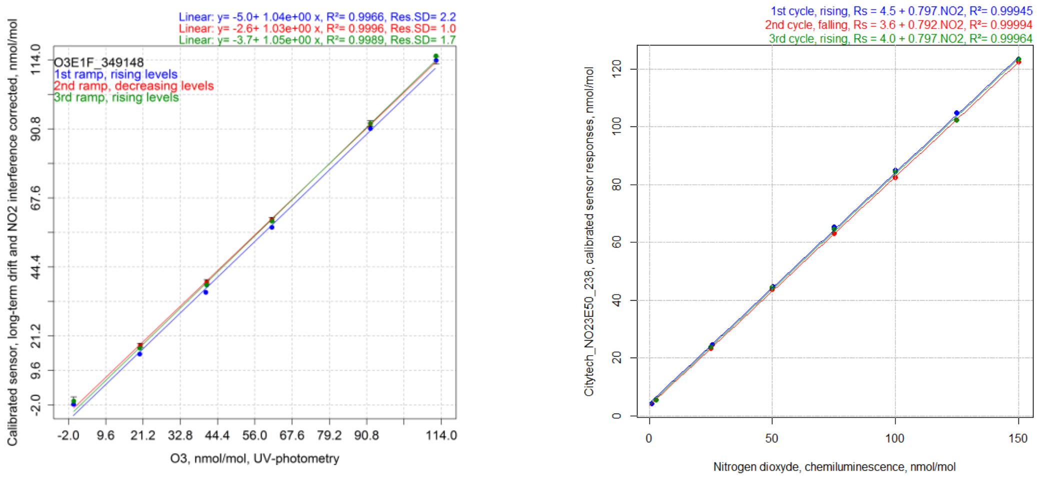


Figure 15: Example of hysteresis effect for the ozone (left column) and NO2 (right column) sensors

7 Conclusion

The AirSensEUR shield offers a route towards an open solution for the air pollution monitoring at low concentration levels using low-costs sensors. The AirSensEUR shield is an open software/open hardware object able to accommodate 4 electrochemical sensors together with 3 auxilliary ambient sensors (temperature, relative humidity and pressure).

In this report, the element needed to use or develop this open object are presented, ease and released. The laboratories experiments demonstrated that after correct configuration, AirSensEUR is sensitive enough to measure sensor responses corresponding to change in ambient air pollution.

The laboratory experiments showed that City Tech sensors mounted on AirSensEUR shield are strongly affected by drift, cross sensitivities and temperature, while humidity effect is limited. Our current objective is to design and apply a correction to these effects on the server side. As the correction maybe different for each sampling site and/or each sensor it will be the responsibility of each user to implement the appropriate correction even though we will thrive to give guidance based on our available knowledge. Collaboration from expert from other institution is welcome.

The first objective is to use AirSensEUR for fixed measurements in order to limit the complexity of the calibration function of the sensors. However, it is also promising technology for the monitoring of population exposure in mobile context. It is likely that mobile measurements is a more challenging objective that will need to develop algorithm able to solve transient change of exposure.

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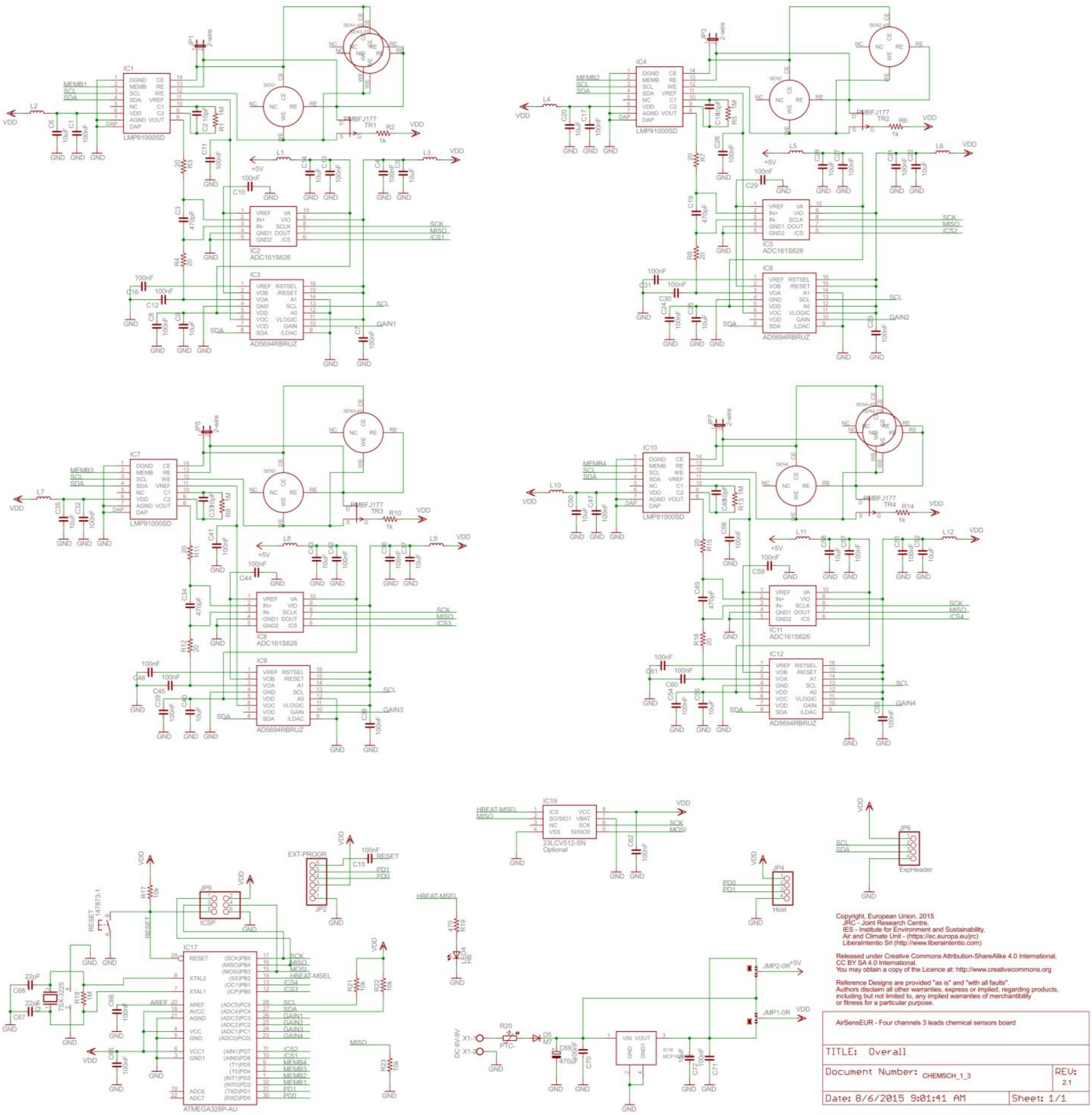
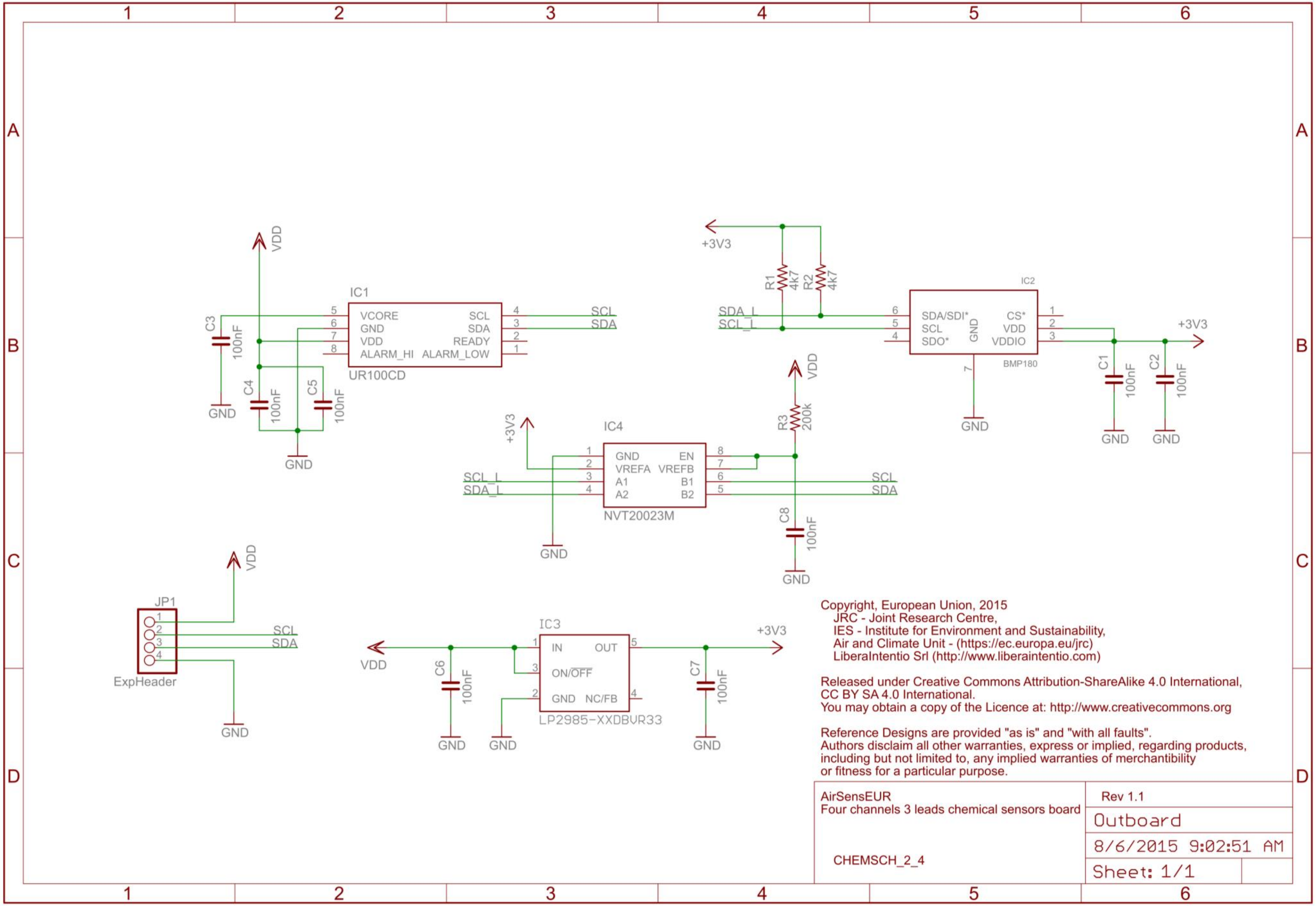
9 Appendix

9.1 Electronic schemes

In the following the overall scheme of the sensor shield, the daughter board and the USB2Serial acquisition board are given

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GND
VDD
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SCL
SDA
READY
ALARM_LOW
VDD
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C5 100nF
GND
+3V3
R1 4k7
R2 4k7
SDA_L
SCL_L
IC2
BMP180
SDA/SDI*
SCL
SDO*
GND
CS*
VDD
VDDIO
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C2 100nF
IC4
NVT20023M
GND
VREFA
A1
A2
EN
VREFB
B1
B2
R3 200k
C8 100nF
JP1
ExpHeader
IC3
LP2985-XXDBVR33
IN
ON/OFF
GND
OUT
NC/FB
C6 100nF
C7 100nF
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AirSensEUR
Four channels 3 leads chemical sensors board
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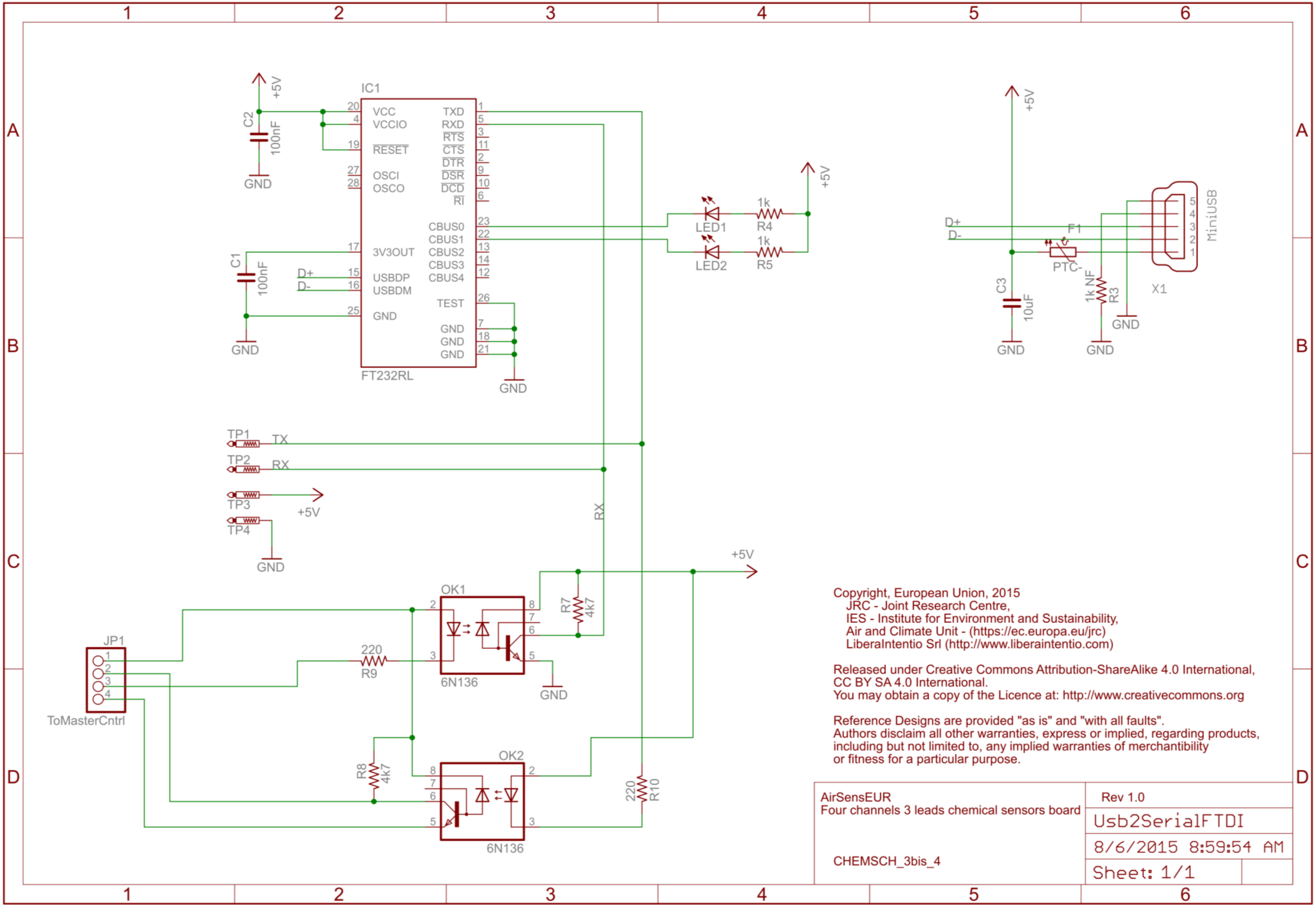

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VCC
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OSCO
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USBDP
USBDM
GND
TXD
RXD
RTS
CTS
DTR
DSR
DCD
RI
CBUS0
CBUS1
CBUS2
CBUS3
CBUS4
TEST
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C2
100nF
C1
100nF
D+
D-
GND
LED1
LED2
1k
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R5
F1
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C3
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AirSensEUR
Four channels 3 leads chemical sensors board
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Rev 1.0
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9.2 List of components

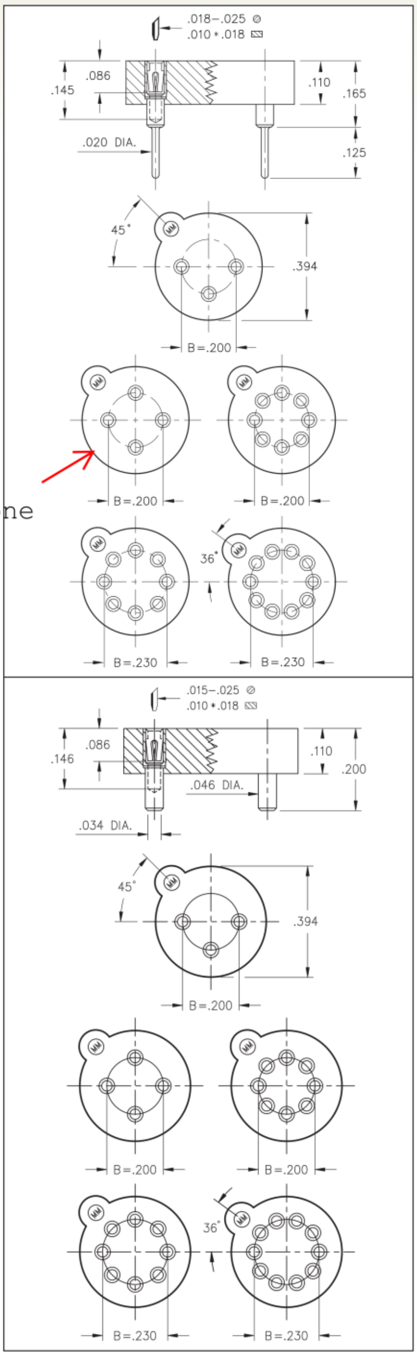
9.2.1 Bill of material

Qty	Mouser, RSComponents, Digikey Codes	Value	Device	Parts								
1	667-ERJ-6GEYJ105V	1M	R_0805	R18								
8	667-ERJ-6GEYJ102V	1k	R_0805	R1,	R2,	R5,	R6,	R9,	R10,	R13,	R14	
4	156-049+674-2375	2-wire	JP1E	JP1,	JP3,	JP5,	JP7					
4	ED90274-ND (917-43-104-41-005000)	3CHEMSEN	3CHEMSEN	SEN1,	SEN2,	SEN3,	SEN4					
4	667-ERJ-6GEYJ103V	10k	R_0805	R17,	R21,	R22,	R23					
4	581-08055A100J	10pF	C_0805	C2,	C18,	C33,	C48					
17	810-C2012X5R1A106K-3	10uF	C_0805	C5,	C6,	C9,	C14,	C20,	C22,	C25,	C28,	
8	660-RK73H2ATTD20R0F	20 1%	R_0805	R3,	R4,	R7,	R8,	R11,	R12,	R15,	R16	
2	581-08055A220J	22pF	C_0805	C67,	C68							
42	80-C0805C104Z5V	100nF	C_0805	C1,	C4,	C7,	C8,	C10,	C11,	C12,	C13,	
1	667-ERJ-6GEYJ471V	470	R_0805	R19								
4	77-VJ0805Y471JXXPBC	470pF	C_0805	C3,	C19,	C34,	C49					
1	140-REA471M1ABK0811P	470uF	CPOL-EUE3.5-10	C69								
1	506-147873-1	147873-1	147873-1	RESET								
4	584-AD5694RBRUZ	AD5694RBRUZ	AD569XRRU	IC3,	IC6,	IC9,	IC12					
4	926-C161S626CIMMNOPB	ADC161S626	ADC161S626	IC2,	IC5,	IC8,	IC11					
1	556-ATMEGA328P-AU	ATMEGA328P-AU	ATMEGA328P-AU	IC17								
12	81-BLM21RK121SN1D	BLM21RK121SN1D	L_0805	L1,	L2,	L3,	L4,	L5,	L6,	L7,	L8,	L9,
1	571-2828372	DC	6V-9V	W237-02P	X1							
1	156-049	EXT-PROGR	PINHD-1X6	JP2								
1	156-049	ExpHeader	PINHD-1X4	JP6								
1	720-LHR974-LP-1	HB	LEDCHIPLED_0805	LED4								
1	156-049	Host	PINHD-1X4	JP4								
4	926-LMP91000SDE/NOPB	LMP91000SD	LMP91000SD	IC1,	IC4,	IC7,	IC10					
1	750-CGRA4007-G	M7	DIODE-DO214AC	D5								
1	579-MCP1825S-5002EDB	MCP1825SDB	MCP1825SDB	IC18								
4	771-PMBFJ177-T/R	PMBFJ177	PMBFJ177	TR1,	TR2,	TR3,	TR4					
1	576-1812L020PR	PTC-	PTC-	R20								
1	732-TX325-16F09Z-AC3	TSX-3225	TSX-3225	Q1								
0	579-23LCV512-I/SN	23LCV512-SN	23LCV512-SN	IC19								

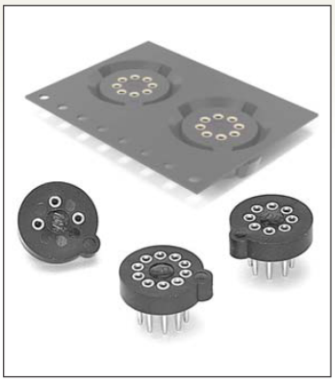
TRANSISTOR SOCKETS

SERIES 917 • SURFACE AND THROUGH-HOLE MOUNT

This one



- Series 917 TO package sockets are available in 3, 4, 8 and 10 positions
- Two 8 pin versions feature pin centers on .200" or .230" circle
- Series 917...005 use MM #1705 and MM #1802 pins, see pages 168 and 169 for details. Receptacles use Hi-Rel, 4 finger #30 contact rated at 3 amps. See page 253 for details
- Series 917...001 uses MM #1701 pins. See page 171 for details. Receptacles use Hi-Rel, 4 finger #30 contact rated at 3 amps. See page 253 for details
- Insulators are high temperature thermoplastic, suitable for all soldering operations
- For Electrical, Mechanical and Environmental Data, see page 264 for details



ORDERING INFORMATION

Transistor Sockets (Through-Hole Mount)

Type	Circle Dia.	Number of Pins	Ordering Information
TO-5	0.200	3	917-XX-103-41-005000
TO-5	0.200	4	917-XX-104-41-005000
TO-5	0.200	8	917-XX-108-41-005000
TO-100	0.230	8	917-XX-208-41-005000
TO-100	0.230	10	917-XX-210-41-005000

Transistor Sockets (Surface Mount)

Type	Circle Dia.	Number of Pins	Ordering Information
TO-5	0.200	3	917-XX-103-41-001000
TO-5	0.200	4	917-XX-104-41-001000
TO-5	0.200	8	917-XX-108-41-001000
TO-100	0.230	8	917-XX-208-41-001000
TO-100	0.230	10	917-XX-210-41-001000

Tape and Reel Packaging: (Surface Mount ONLY)

Ordering Information: 917-XX-XXX-41-001799

Available on 24mm wide tape, 730 parts per 13" reel

XX=Plating Code See Below

RoHS-2 2011/65/EU

SPECIFY PLATING CODE XX=		91	93		41	43	
Sleeve (Pin)		200 µ"Sn/Pb	200 µ"Sn/Pb		200 µ"Sn	200 µ"Sn	
Contact (Clip)		10 µ"Au	30 µ"Au		10 µ"Au	30 µ"Au	

MILL-MAX Mill-Max Mfg. Corp. • 190 Pine Hollow Road, P.O. Box 300, Oyster Bay, NY 11771 • 516-922-6000 • Fax: 516-922-9253 • www.mill-max.com

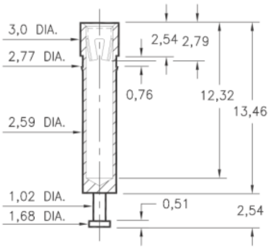
See or https://www.mill-max.com/new_products/detail/63

PIN RECEPTACLES

FOR 1,22 - 1,63 DIAMETER PINS (#13 CONTACT)
FOR 1,14 - 1,65 DIAMETER PINS (#23 CONTACT)

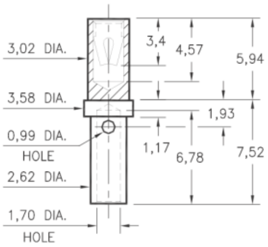
0496
0496-0-15-XX-23-XX-10-0

Press-fit in 2,69 mounting hole



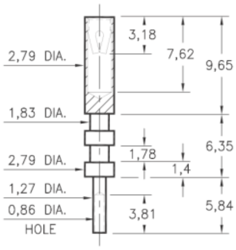
0368
0368-0-33-XX-13-XX-10-0

Wire crimp termination. Accepts wire sizes 16 AWG Max. / 20 AWG Min.



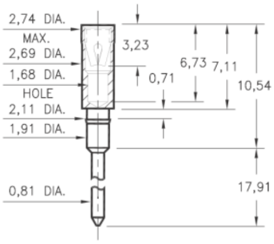
8067
8067-0-19-XX-13-XX-10-0

Wire Termination. Accepts wire sizes 24 AWG Max. / 28 AWG Min.



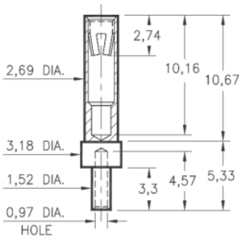
1105
1105-0-15-XX-13-XX-04-0

Press-fit in 2,03 mounting hole



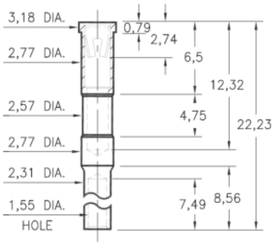
8730
8730-0-19-XX-23-XX-10-0

Wire crimp termination. Accepts wire sizes 22 AWG Max. / 26 AWG Min.



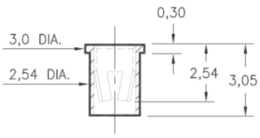
3667
3667-0-19-XX-23-XX-10-0

Wire crimp termination. Accepts wire sizes 18 AWG Max. / 22 AWG Min.



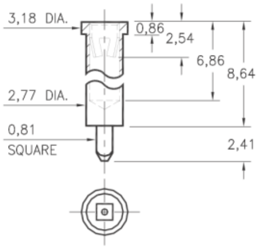
9372
9372-0-15-XX-23-XX-10-0

Solder mount in 2,59 min. mounting hole



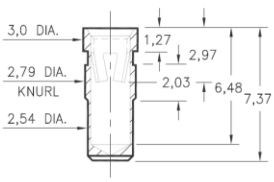
4582
4582-0-15-XX-23-XX-10-0

Square press-fit in 1,02 plated through-hole



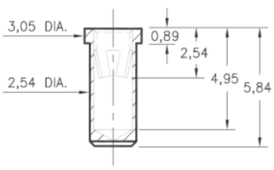
5834
5834-0-15-XX-23-XX-10-0

Press-fit in 2,72 mounting hole



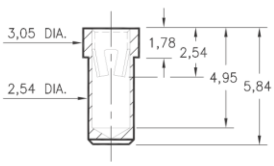
9401
9401-0-15-XX-23-XX-10-0

Solder mount in 2,59 min. mounting hole
Also available on 24mm wide carrier tape:
1,100 parts per 330mm reel
Order as: 9401-0-57-XX-23-XX-10-0



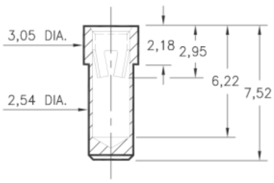
9801
9801-0-15-XX-23-XX-10-0

Solder mount in 2,59 min. mounting hole
Also available on 16mm wide carrier tape:
1,200 parts per 330mm reel
Order as: 9801-0-57-XX-23-XX-10-0



8829
8829-0-15-XX-23-XX-10-0

Solder mount in 2,59 min. mounting hole



SPECIFICATIONS:

Shell Material: Brass Alloy 360, 1/2 Hard

Contact Material: Beryllium Copper Alloy 172, HT

Dimensions: Millimeters

Tolerances On: Lengths: ± 0,13
Diameters: ± 0,051
Angles: ± 2°

RoHS-2 2011/65/EU

ORDER CODE: XXXX - X - XX - XX - XX - XX - XX - 0

BASIC PART #

SPECIFY SHELL FINISH:
- **01** 5,08µm TIN/LEAD OVER NICKEL
- **80** 5,08µm TIN OVER NICKEL (RoHS)
- **15** 0,25µm GOLD OVER NICKEL (RoHS)

SPECIFY CONTACT FINISH:
- **01** 5,08µm TIN/LEAD OVER NICKEL
- **80** 5,08µm TIN OVER NICKEL (RoHS)
- **27** 0,76µm GOLD OVER NICKEL (RoHS)

SELECT CONTACT:
#13 or #23 CONTACT (DATA ON PAGE 260)
(For alternate contact choices, see group G on page 248)

Mill-Max Mfg. Corp. • 190 Pine Hollow Road, P.O. Box 300, Oyster Bay, NY 11771 • 516-922-6000 • Fax: 516-922-9253 • www.mill-max.com

9.2.3 Temperature humidity sensor

UR100CD

UR100CD

Humidity & Temperature Solution

Features

- Fully Calibrated & Temperature Compensated
- Digital or Analog Output with Alarm Function
- Precision & Accuracy (±2%RH, ±0.3°C, 14 bit)
- Free Operating Voltage (min 2.3V to max 5.5V)
- Low Current Consumption
- SMD Package for Automated Assembly
- Reliable in Harsh Environment

Product Summary

UR100CD offers the most advanced and cost effective humidity and temperature sensing solution for virtually any type of applications.

Capacitive polymer sensor chip developed and fabricated in-house and CMOS integrated circuit

Individually calibrated and tested, UR100CD performs ±2% from 20% to 80%RH (entire humidity range), and yet, is simple and ready to use without further calibration or temperature compensation.

UR100CD provides linear output signals in various interfaces to customer requirements I2C interface, PDM convertible to analog signal, an Alarm function for preset control at min/max humidity.

Tecnosens Spa
Via Vergnano, 16 – 25125 Brescia (BS) ITALY
Tel: +39.030.3534144 - Fax: +39.030.3530815 – web: www.tecnosens.it – mail: info@tecnosens.it

Application

Energy Saving HVAC Control

Air Conditioning, Refrigeration, IAQ monitoring, Vent Fans, Home Appliances, Humi/Dehumidi-

Process Control & Instrumentations

Medical Instruments, Handheld Devices Stations, Food Processing, Printers, RFIDs

Automobile & Transportation

Cabin Climate Control, Defogging Control Condensing Preventive Devise

Mass Quantity Application

Sensor Performance

Relative Humidity (RH%)

* Custom Accuracy Tolerance Available

Resolution	**14 bit** (0.01%RH)
Accuracy[1]	**±2.0** %RH (20~80%RH)*
Repeatability	**±0.2** %RH
Hysteresis	**±2.0** %RH
Linearity	**<2.0** %RH
Response time[2]	**7.0** sec (τ 63%)
Temp Coefficient	**Max 0.13** %RH/℃ (at 10~60℃, 10~90%RH)
Operating range	**0 ~ 100** %RH (Non-Condensing)
Long term drift	**<0.5** %RH/yr (Normal condition)

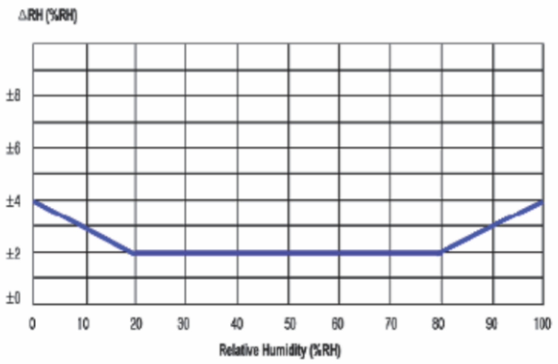


Figure 1. Typical RH% Accuracy at 25°C

UR100CD

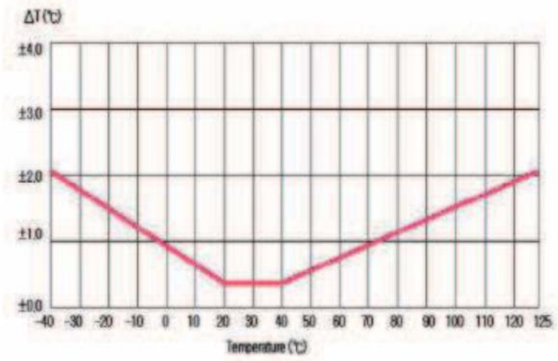
Temperature (°C)

Resolution	**14 bit** (0.01℃)
Accuracy[3]	**±0.3 ℃** **(Figure 2)**
Repeatability	**±0.1 ℃**
Response time[4]	**5.0** sec (τ 63%)
Operating range	**- 40 ~ 125 ℃**
Long term drift	**<0.05** ℃/yr (Normal condition)

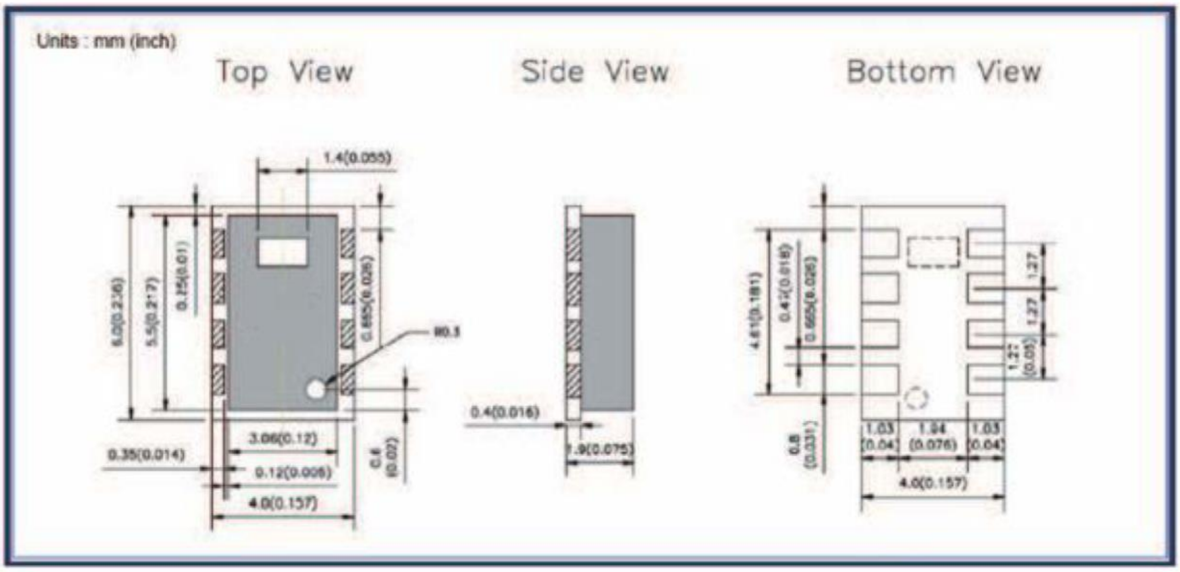
1. Accuracies measured at 25°C, 5.0V.

63% of step from 33%RH to 90%RH
3. Accuracies measured at 25°C, 5.0V.
4. Min 5.0 sec, Max 20 sec

Figure 2. Typical Temperature Accuracy

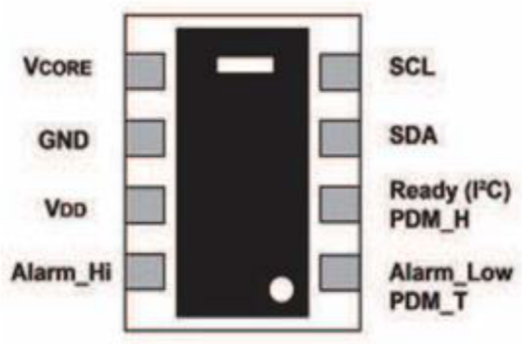


Dimensions



UR100CD

Pin Connection



Supply Voltage*1	min 2.3V ~ max 5.5V
Supply Current (IDD)	750 μA (typical)
Sleep Current (Isleep)*2	0.6 μA (typical)

*1. Lower than 2.7V supply voltage may increase the accuracy tolerance of the Temperature
*2. at -40 ~ 85°C

Package Contents

Capacitive polymer RH Sensor, PTA (Proportional to Absolute) Temperature sensor integrated ASIC chip in LCC (Leadless Chip Carrier) package, SMD.
RoHS Compliant

Environmental

Operating Temperature	- 40 ~ 125℃
Operating Humidity	0~100%RH (non condensing)

Absolute Maximum Rating

Parameter	Min	Max
Supply Voltage (VDD)	**-0.3V**	**6.0V**
Storage Temp	**-55℃**	**150℃**
Junction Temp	**-55℃**	**150℃**

Soldering Information

Sipphing

Reel & Tape: 2,500 / 500 ea

9.3 Sensors brands and models for AirSensEUR shield (updated on 15/08/2015)

Alphasense[28]

Pollutant	Type	Model	Sensitivity, nA/ppm	Description	Download
Carbon Monoxide	A/Miniature/4	CO-AE	10 to 25	Small, filtered, high concentration	
		CO-AF	55 to 90	Small, filtered	
		CO-AX	55 to 100	Small, low hydrogen cross sensitivity	
		CO-CE	10 to 25	Combustion, high concentration	
		CO-CF	55 to 90	Combustion, filtered	
		CO-CX	55 to 100	Combustion, low hydrogen cross sensitivity	
	B/Compact/7	CO-BF	80 to 130	Compact, filtered	
		CO-BX	70 to 130	Compact, low hydrogen cross sensitivity	
Chlorine	A/Miniature/4	CL2-A1	-350 to -750	Small	
	B/Compact/7	CL2-B1	-600 to -1150	Compact	
Ethylene oxide	A/Miniature/4	ETO-A1	-600 to -1150	Small	
	B/Compact/7	ETO-B1	2000 to 3200	Compact	
Hydrogen	A/Miniature/4	H2-AF	10 to 20	Small	
	B/Compact/7	H2-BF	10 to 25	Compact	
Hydrogen chloride	A/Miniature/4	HCL-A1	80 to 130	Small	
	B/Compact/7	HCL-B1	150 to 250	Compact	
Hydrogen cyanide	A/Miniature/4	HCN-A1	55 to 85	Small	
	B/Compact/7	HCN-B1	80 to 140	Compact	
Ammonia	B/Compact/7	NH3-B1	25 to 45	Compact	
Phosphine	A/Miniature/4	PH3-A1	550 to 900	Small	
	B/Compact/7	PH3-B1	600 to 1000	Compact	
		PH3-BE	15 to 35	Compact, high concentration	
Hydrogen Sulfide	A/Miniature/4	H2S-A1	550 to 875	Small	
		H2S-AE	65 to 105	Small, high concentration	
		H2S-AH	950 to 1450	Small, high sensitivity	
	B/Compact/7	H2S-B1	300 to 450	Compact, unfiltered	
		H2S-BE	80 to 115	Compact, high concentration	
		H2S-BH	1500 to 2100	Compact, high sensitivity	
Nitrogen monoxide	A/Miniature/4	NO-A1	320 to 480	Small	
		NO-AE	40 to 80	Small, high concentration	
	B/Compact/7	NO-B1	400 to 620	Compact, filtered	
Nitrogen Dioxide	A/Miniature/4	NO2-A1	-250 to -650	Small	
		NO2-AE	-100 to -170	Small, high concentration	
	B/Compact/7	NO2-B1	-450 to -1000	Compact, unfiltered	
Sulfur Dioxide	A/Miniature/4	SO2-AE	80 to 120	Small, high-concentration	
		SO2-AF	400 to 650	Small, filtered	
	B/Compact/7	SO2-BE	70 to 85	Compact, high-concentration	
		SO2-BF	300 to 480	Compact, filtered	

City technology [25]

Pollutant	Type	Model	Sensitivity, nA/ppm	Description	Download
Carbon Monoxide	Sensoric	CO 3E 500 S	70 ± 20	3 Electrode sensor	
		CO 2E 300	30 ± 12	2 Electrode sensor	
		CO 3E 300	70 ± 20	3 Electrode sensor	
	A/Miniature/4	4F	70 ±15	3 electrode electrochemical with filter to remove acid gases	
		4MF	15 ± 5	3 electrode electrochemical	
		2CF	50 ± 20	2 Electrode minature sensor	
		4CF+	70 ± 15	3 – electrode miniature sensor	
	B/Compact/7	7E	100 ± 20	3 Electrode compact sensor	
		7E/F	100 ± 20	3 Electrode compact sensor with H2S and SO2 filter	
Ethylene oxide	A/Miniature/4	4ETO	1900 ± 500	3 Electrode minature sensor	
	B/Compact/7	7ETO	2250 ± 650	3 Electrode compact sensor	
Ammonia	Sensoric	NH3 3E 100	90 ± 40	3 Electrode sensor with organic electrolyte	
	Sensoric	NH3 3E 100 SE	130 ± 30	3 Electrode sensor	
	Sensoric	NH3 3E 1000	8 ± 4	3 Electrode sensor with organic electrolyte	
	Sensoric	NH3 3E 1000 SE	8 ± 4	3 Electrode sensor	
	Sensoric	NH3 3E 500 SE	35 ± 15	3 Electrode sensor	
	Sensoric	NH3 3E 5000 SE	4 ± 2	3 Electrode sensor	
Nitrogen monoxide	Sensoric	NO 3E 100	45 ± 15	3 Electrode sensor	
	4 Series	4NT	400 ± 80	3 Electrode minature sensor	
	7 Series	7NT	550 ± 110	3 Electrode compact sensor	
Nitrogen Dioxide	Sensoric	NO2 3E 50	200 ± 40	3 Electrode sensor with organic electrolyte;	
	4 Series	4ND	600 ± 150	3 Electrode minature sensor	
	7 Series	7NDH	1400 ± 300	3 Electrode compact sensor	
Ozone	Sensoric	O3 3E 1	1000 - 2000	3 Electrode sensor with organic electrolyte	
		O3 3E 1 F	450 ± 150		
	B/Compact/7	7OZ	7200 ± 2300	3 Electrode compact sensor	
Sulfur Dioxide	A/Miniature/4	4S Rev. 2	500 ± 100	3 Electrode sensor with H2S filter	
	B/Compact/7	7SH	1250 ± 250	3 Electrode compact sensor	
		7ST/F	370 ± 70	3 Electrode sensor with H2S filter	

Membrapor [27]

Pollutant	Type	Model	Sensitivity, nA/ppm	Description	Download
Br2, Bromine /Cl2, chlorine	A/Miniature/4	Cl2/M-20	600.0 ± 150.0	3-electrode sensor, highly sensitive	
		Cl2/M-200	120.0 ± 30.0	3-electrode sensor	
		Cl2/M-2EG	280.0 ± 80.0	2-electrode sensor	
	B/Compact/7	Cl2/C-20	900.0 ± 250.0	3-electrode sensor highly sensitive	
		Cl2/C-5000	4.0 ± 1.0	3-electrode sensor	
CH2O, Formaldehyde	A/Miniature/4	CH2O/M-10	4600.0 ± 1200.0	3-electrode sensor, highly sensitive	
		CH2O/M-10-2E	2300.0 ± 800.0	2-electrode sensor	
		CH2O/M-1000	60.0 ± 15.0	3-electrode sensor	
		CH2O/M-20-2E	1000.0 ± 500.0	2-electrode sensor	
	B/Compact/7	CH2O/C-10	4600.0 ± 1200.0	3-electrode sensor, highly sensitive	
C2H4, Ethene, Ethylene	A/Miniature/4	C2H4/M-10	400.0 ± 300.0	3-electrode sensor, highly sensitive	
		C2H4/M-1500	12.0 ± 4.0	3-electrode sensor	
		C2H4/M-200	65.0 ± 25.0	3-electrode sensor	
	B/Compact/7	C2H4/C-10	400.0 ± 120.0	3-electrode sensor, highly sensitive	
		C2H4/C-1500	12.0 ± 4.0	3-electrode sensor	
		C2H4/C-200	100.0 ± 30.0	3-electrode sensor	
C2H4O, Ethylene Oxide	A/Miniature/4	ETO/M-10	1900.0 ± 400.0	3-electrode sensor, highly sensitive	
		ETO/M-100	200.0 ± 40.0	3-electrode sensor	
		ETO/M-1000	25.0 ± 6.0	3-electrode sensor	
		ETO/M-20	1000.0 ± 200.0	3-electrode sensor, highly sensitive	
		ETO/M-500	50.0 ± 15.0	3-electrode sensor	
	B/Compact/7	ETO/C-100	200.0 ± 40.0	3-electrode sensor	
		ETO/C-1000	50.0 ± 15.0	3-electrode sensor	
		ETO/C-20	2200.0 ± 600.0	3-electrode sensor, highly sensitive	
		ETO/C-5000	15.0 ± 8.0	3-electrode sensor	
R3COH, Alcohols	A/Miniature/4	Alc/M-200	1000.0 ± 250.0	Methanol / Ethanol Measurement	
CO, Carbon Monoxide	A/Miniature/4	CO/MF-1000	50.0 ± 15.0	3-electrode sensor with filter	
		CO/MF-200	500.0 ± 150.0	3-electrode sensor with filter	
		CO/MF-2000	30.0 ± 5.0	3-electrode sensor with filter	
		CO/MF-2E	50.0 ± 15.0	2-electrode sensor	
		CO/MF-500	70.0 ± 20.0	3-electrode sensor with filter	
		CO/MFA-500	70.0 ± 15.0	3-electrode sensor	

				highly selective	
	B/Compact/7	CO/C-1000	100.0 ± 20.0	3-electrode sensor	
		CO/C-200	900.0 ± 150.0	3-electrode sensor highly sensitive	
		CO/CF-1000	100.0 ± 20.0	3-electrode sensor with filter	
		CO/CF-200	700.0 ± 120.0	highly sensitive, with filter	
		CO/CF-200-4E	470.0 ± 120.0	Hydrogen compensated	
		CO/CF-2000	50.0 ± 10.0	Emission Monitoring	
		CO/CF-2000-4E	80.0 ± 25.0	Hydrogen compensated	
		CO/CF-4000	30.0 ± 6.0	Emission Monitoring	
		CO/CF-40000	6.0 ± 2.0	Emission Monitoring	
		CO/CF-500	160.0 ± 30.0	with filter	
		CO/CFA-1000	100.0 ± 20.0	highly selective	
		CO/CFA-10000	15.0 ± 4.0	highly selective	
		CO/CFA-500	160.0 ± 30.0	highly selective	
		CO/CFA-5000	30.0 ± 5.0	highly selective	
		CO/CFL-4E	700.0 ± 120.0	for lowest gas concentrations	
H2, Hydrogen	A/Miniature/4	H2/M-1000	25.0 ± 10.0	3-electrode sensor highly sensitive	
		H2/M-4000	10.0 ± 6.0	3-electrode sensor	
		H2/M-40000	7.0 ± 4.0	3-electrode sensor	
	B/Compact/7	H2/C-2000	23.0 ± 8.0	3-electrode sensor highly sensitive	
		H2/C-20000	8.0 ± 3.0	3-electrode sensor	
		H2/C-5000	9.5 ± 2.5	3-electrode sensor	
		H2/CA-1000	28.5 ± 11.5	3-electrode sensor highly selective	
		H2/CB-1000	28.5 ± 11.5	3-electrode sensor more gastight	
		H2/CT-10000	15.0 ± 6.0	3-electrode sensor at high humidity	
		H2/CT-40000	5.5 ± 2.0	at high humidity	
H2S, Hydrogen Sulfide	A/Miniature/4	H2S/M-100	700.0 ± 140.0	3-electrode sensor	
		H2S/M-200-2E	250.0 ± 50.0	2-electrode sensor	
		H2S/M-2000	50.0 ± 10.0	3-electrode sensor	
		H2S/M-50	1200.0 ± 250.0	3-electrode sensor highly sensitive	
		H2S/M-500	100.0 ± 20.0	3-electrode sensor	
	B/Compact/7	H2S/C-1000	100.0 ± 20.0	3-electrode sensor	
		H2S/C-200	370.0 ± 80.0	3-electrode sensor	
		H2S/C-2000	50.0 ± 9.0	3-electrode sensor	
		H2S/C-50	1700.0 ± 300.0	3-electrode sensor highly sensitive	
		H2S/C-500	200.0 ± 40.0	3-electrode sensor	

		H2S/C-5000	26.0 ± 6.0	3-electrode sensor
		H2S/CP-100	550.0 ± 110.0	more gastight
		H2S/CP-10000	15.0 ± 5.0	more gastight
		H2S/CP-2000	50.0 ± 9.0	more gastight
		H2S/CP-500	200.0 ± 40.0	more gastight
		H2S/CP-5000	25.0 ± 6.0	more gastight
HBr, Hydrogen Bromide / HCl, Hydrogen Chloride	A/Miniature/4	HCl/M-20	400.0 ± 150.0	3-electrode sensor highly sensitive
		HCl/M-200	80.0 ± 30.0	short response time
	B/Compact/7	HCl/C-1000	20.0 ± 5.0	short response time
		HCl/C-20	450.0 ± 150.0	highly sensitive
		HCl/C-200	100.0 ± 35.0	short response time
HCN, Hydrogen Cyanide	A/Miniature/4	HCN/M-100	140.0 ± 40.0	short response time
		HCN/M-50	200.0 ± 50.0	short response time highly sensitive
	B/Compact/7	HCN/C-100	600.0 ± 150.0	3-electrode sensor highly sensitive
H2O2, Hydrogen Peroxide	B/Compact/7	H2O2/CB-100	1100.0 ± 150.0	3-electrode sensor highly sensitive
		H2O2/CB-2000	50.0 ± 10.0	3-electrode sensor
		H2O2/CB-500	200.0 ± 50.0	3-electrode sensor
NH3, Ammonia	A/Miniature/4	NH3/MR-100	110.0 ± 30.0	3-electrode sensor highly sensitive
		NH3/MR-100-2E	50.0 ± 12.0	2-electrode sensor
		NH3/MR-1000	25.0 ± 9.0	3-elect. sensor short response time
		NH3/MR-1000-2E	19.0 ± 7.0	2-electrode sensor
		NH3/MR-10000	2.5 ± 0.6	3-electrode sensor
		NH3/MR-2000	12.0 ± 4.0	3-elect. sensor short response time
		NH3/MR-500	35.0 ± 15.0	3-elect. sensor short response time
		NH3/MR-5000	5.0 ± 1.8	3-elect. sensor short response time
	B/Compact/7	NH3/CR-1000	25.0 ± 8.0	3-elect. sensor short response time
		NH3/CR-10000	2.5 ± 0.5	3-elect. sensor short response time
		NH3/CR-200	112.0 ± 40.0	3-electrode sensor highly sensitive
		NH3/CR-5000	6.0 ± 2.0	3-elect. sensor short response time
NO, Nitric Oxide	A/Miniature/4	NO/M-1000	100.0 ± 25.0	3-electrode sensor
		NO/M-25	1000.0 ± 400.0	3-electrode sensor highly sensitive
		NO/M-250	360.0 ± 80.0	3-electrode sensor
	B/Compact/7	NO/C-1	5000.0 ± 2000.0	3-electrode sensor highly sensitive
		NO/C-100	550.0 ± 110.0	3-electrode sensor

		NO/C-25	2000.0 ± 400.0	3-electrode sensor highly sensitive	
		NO/CF-100	400.0 ± 80.0	3-electrode sensor with filter	
		NO/CF-2000	100.0 ± 20.0	Emission Monitoring	
NO2, Nitrogen Dioxide	A/Miniature/4	NO2/M-100	120.0 ± 30.0	3-electrode sensor	
		NO2/M-20	600.0 ± 150.0	3-electrode sensor highly sensitive	
		NO2/M-2E	300.0 ± 70.0	2-electrode sensor	
		NO2/M-2EG	300.0 ± 70.0	2-electrode sensor	
	B/Compact/7	NO2/C-1	2500.0 ± 1000.0	3-electrode sensor highly sensitive	
		NO2/C-20	1100.0 ± 300.0	3-electrode sensor highly sensitive	
		NO2/C-500	370.0 ± 70.0	Emission Monitoring	
O2, Oxygen	A/Miniature/4	O2/M-1	1300.0 ± 300.0	3-elect. sensor short response timeS	
		O2/M-100	100.0 ± 24.0	3-elect. sensor short response time	
O3, Ozone	A/Miniature/4	O3/M-100	400.0 ± 50.0	3-electrode sensor	
		O3/M-5	1000.0 ± 350.0	3-electrodes, highly sensitive	
	B/Compact/7	O3/C-100	650.0 ± 150.0	3-electrode sensor	
		O3/C-1000	170.0 ± 30.0	3-electrode sensor	
		O3/C-2	3000.0 ± 1200.0	3-electrode sensor highly sensitive	
		O3/C-200	400.0 ± 130.0	3-electrode sensor	
		O3/C-5	1500.0 ± 500.0	3-electrode sensor highly sensitive	
		O3/C-5000	30.0 ± 10.0	3-electrode sensor	
PH3, Phosphine	A/Miniature/4	PH3/M-20	1000.0 ± 300.0	3-elect. sensor short response time	
		PH3/M-2000	50.0 ± 15.0	3-elect. sensor short response time	
		PH3/M-5	3500.0 ± 1000.0	3-electrode sensor highly sensitive	
	B/Compact/7	PH3/C-1000	100.0 ± 25.0	3-elect. sensor short response time	
		PH3/C-2000	70.0 ± 20.0	3-elect. sensor short response time	
		PH3/C-4000	30.0 ± 8.0	3-elect. sensor short response time	
		PH3/C-5	4000.0 ± 1200.0	3-electrode sensor highly sensitive	
		PH3/C-500	200.0 ± 50.0	3-elect. sensor short response time	
SiH4, Silane	A/Miniature/4	SiH4/M-50	500.0 ± 60.0	3-electrode sensor highly sensitive	
	B/Compact/7	SiH4/C-50	1000.0 ± 300.0	3-electrode sensor	
SO2, Sulfur Dioxide	A/Miniature/4	SO2/M-100-2E	300.0 ± 80.0	2-electrode sensor	
		SO2/M-20	500.0 ± 90.0	3-electrode sensor highly sensitive	

		SO2/M-2E	450.0 ± 80.0	2-electrode sensor	
		SO2/MF-100	370.0 ± 70.0	3-electrode sensor with filter	
		SO2/MF-1000	50.0 ± 10.0	3-electrode sensor with filter	
		SO2/MF-10000	20.0 ± 5.0	3-electrode sensor	
		SO2/MF-20	500.0 ± 90.0	highly sensitive, with filter	
		SO2/MF-2000	25.0 ± 5.0	3-electrode sensor with filter	
	B/Compact/7	SO2/C-1	5000.0 ± 2000.0	3-electrode sensor highly sensitive	
		SO2/C-100	370.0 ± 70.0	3-electrode sensor	
		SO2/C-20	1000.0 ± 300.0	3-electrode sensor highly sensitive	
		SO2/C-2000	100.0 ± 20.0	3-electrode sensor	
		SO2/CF-100	370.0 ± 70.0	3-electrode sensor with filter	
		SO2/CF-10000	20.0 ± 5.0	3-electrode sensor with filter	
		SO2/CF-20	550.0 ± 150.0	highly sensitive, with Filter	
		SO2/CF-2000	100.0 ± 20.0	Emission Monitoring	

SGX Sensortech [26]

Pollutant	Type	Model	Sensitivity, nA/ppm	Description	
Carbon Monoxide	4-Series	EC4-500-CO	70 ± 15	3 Electrode sensor	http://www.sgxsensortech.com/sensor-selector/#collapse-datasheets-1
		SGX-4CO	70 ± 25	3 electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/10/DS-0138-SGX-4CO-V1.pdf
		EC4-2000-CO	28 ± 10	3 electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/EC4-2000-CO1.pdf
	7-Series	SGX-7CO	100 ± 20	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/DS-0144-SGX-7CO-V2.pdf
Ethylene oxide	B or 4-Series	EC4-10-ETO	1900 ± 800	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/DS-0201-EC4-10-ETO-Datasheet-V1.pdf
Ammonia	B or 4 Serie	SGX-4NH3	100 ± 30	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2015/04/DS-0199-SGX-4NH3-V2.pdf
	A or 7 series	SGX-7NH3	115 ± 45	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/DS-0146-SGX-7NH3-V5.pdf
Nitrogen monoxide	B or 4 Series	EC4-250-NO	400 ± 80	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/EC4-250-NO1.pdf
	B or 4 Series	EC4-2000-NO	43 ±22	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/EC4-2000-NO1.pdf
	A or 7 Series	SGX-7NH3	115 ±45	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/DS-0146-SGX-7NH3-V5.pdf
Nitrogen Dioxide	B or 4 Series	EC4-20-NO2	600 ± 150	3 Electrode compact sensor	http://www.sgxsensortech.com/content/uploads/2014/07/EC4-20-NO21.pdf
Sulfur Dioxide	B or 4-Series	EC4-20-SO2	400 ± 200	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/EC4-20-SO21.pdf
	B or 4-Series	EC4-2000-SO2	14 ± 6	3 Electrode sensor	http://www.sgxsensortech.com/content/uploads/2014/07/EC4-2000-SO21.pdf

9.4 Communication protocol

9.4.1 AirSensEUR Communication Protocol overview

This document describes the communication protocol implemented by *AirSensEUR*, the chemical sensors board R20 and associated firmware release.
Author: Marco Signorini
Document Revision: 1.2 – 2015/04/04

9.4.2 Physical Layer

The communication with the board is made through a serial line running at 9600bps, 8 bit, no parity. Line level is 5V (TTL). An opto-coupled bi-directional insulated USB adapter is provided with the board to easily connect the board to a host PC.

9.4.3 Communication syntax

The board could accept a set of commands. Each command set is identified by a frame. A frame is limited by a set of braces containing a letter and two or more digits. Commands are identified by a letter and are case sensitive. Optional parameters are encoded with hexadecimal values.
The board acknowledges each command by repeating the command itself and appending result values, if any. Each error or not valid command is acknowledged by the general string `{*}`

9.4.4 Start and stop commands

Start sampling
Purpose: Start the sampling process
Command: S
Parameters: None
Returns: An acknowledgement of the command as soon as the sampling process started
Example:

    Tx: {S}
    Rx: {S}

Stop sampling
Purpose: Stop the sampling process
Command: X
Parameters: None
Returns: An acknowledgement of the command as soon as the sampling process stopped
Example:

    Tx: {X}
    Rx: {X}

9.4.5 Read commands:

Sensor Name Inquiry
Purpose: Retrieve the channel name associated to a sensor
Command: I
Parameters:
    Byte1: the sensor channel ID (from 0 to 6)
Returns:
    Byte1: the sensor channel ID (from 0 to 6)
    Byte2 to 9: the name of the selected channel sensor
Example:

    Tx: {I00}   Inquiry name for sensor 00
    Rx: {I004E4F2033452031}   Name for sensor 00 is "NO 3E 1"

Echo command
Purpose: Check the connection with the board
Command: E
Parameters: None

Returns: A replica of the incoming frame. Useful for connection test.
Example:

Tx: {E}
Rx: {E}

Get the Prescaler size

Purpose: Retrieve the time base associated to the specified sampler channel
Command: Q
Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Returns:

Byte1: the sensor channel ID (from 0 to 6)
Byte2: The time base associated to the specified sampler channel

Example:

Tx: {Q00} Get the sample time base associated to the channel 0
Rx: {Q0031} The sample time for the channel 00 is 0.5s (31hex is 49 decimal → one sample each (49+1)*10ms)s

Get IIR denominators

Purpose: Each sample is filter by two single order IIR filters where the denominator values could be set. The denominator is always a value multiple of 2. This command reads the denominators set for the IIR filters.
Command: B
Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Returns: A frame containing:

Byte1: channel ID referring to
Byte2: the denominator for the 1st IIR filter
Byte3: the denominator for the 2nd IIR filter

Example:

Tx: {B00} Read the IIR denominators for the channel 0
Rx: {B000204} The IIR denominators for the channel 0 are, respectively, 2 and 4

Get the decimation filter size

Purpose: each filtered sample is decimated by a decimation filter. This command reads the size of the decimation filter.
Command: F
Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Returns:

Byte1: the sensor channel ID (from 0 to 6)
Byte2: the decimation filter size (from 0: filter disabled, to 255: take one sample each 255 incoming samples)

Example:

Tx: {F03} Get the decimation filter size for the channel 3
Rx: {F0300} The decimation filter for channel 3 is disabled

Read the averager filter size

Purpose: Each sample extracted from the decimation filter is averaged by mean of a moving average filter. This command read the size of the moving average window
Command: N
Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Returns:

Byte1: the sensor channel ID (from 0 to 6)
Byte2: the average filter size in sample units.

Example:

Tx: {N00} Get the averager length for the channel 0
Rx: {N003C} The averager length for channel 0 is 60 samples

Read Analog Front End setup

Purpose: Each chemical sensor channel is equipped by a programmable analog front end implemented by the LMP91000 integrated circuit. This command reads the internal registers for the specified channel AFE. Details on values be assigned to the internal registers are reported on the device datasheet.

Command: T

Parameters:

Byte1: the chemical sensor channel ID (from 0 to 3)

Returns:

Byte1: the chemical sensor channel ID (from 0 to 3)
Byte2: TIA register value
Byte3: REF register value
Byte4: MODE register value

Example:

Tx: {T00}
Rx: {T001F9603} The channel 0 analog front end is configured as:

Gain: 350 kOhm
Load: 100 Ohm
Reference: External
Internal zero: 20%
Bias polarity: Positive
Bias percentage: 10%
Shorting FET: disabled
Working mode: 3-lead amp cell

Read reference voltages

Purpose: Each chemical sensor channel is equipped with a precise programmable three channel voltage reference generator. This command reads the generator registers.

Command: H

Parameters:

Byte1: the chemical sensor channel ID (from 0 to 3)
Byte2: the voltage reference ID to be programmed.

00: Vin- A/D input
01: Vref A/D
02: LMP91000 external VREF

Returns:

Byte1: the chemical sensor channel ID (from 0 to 3)
Byte2: the voltage reference ID to be programmed.

00: Vin- A/D input
01: Vref A/D
02: LMP91000 external VREF

Byte3-4: a value representing the voltage to be generated (range: 0-4095)
Byte5: the overall output stage multiplier

00: x1 (output voltage is 0-2.5V)
01: x2 (output voltage is 0-5V)

Example:

Tx: {H0300} Retrieve the reference applied to the third channel A/D input VIn-
Rx: {H0300029A00} The reference is 0.415V (Gain = 1; Value = 2A9hex = 681dec
→ V = 2.5V*(681/4096) = 0.415V)

Read last sample

Purpose: Retrieve the last sample for the specified channel. The read value is the result of the sample and processing chain composed by the IIRs, decimation and moving average filters.

Command: G

Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Returns:

Byte1: the sensor channel ID (from 0 to 6)
Byte2-3: the last sample, as 16 bit unsigned value
Byte4-7: the timestamp for the taken sample (as 32 bit unsigned value) in 10ms units

Example:

Tx: {G01} Get last sample for channel 1

Rx: {G01FBC4001200B2} Last sample is 0xFBC4 taken at 0x001200B2

NOTE: The last sample value ranges from 0 to 65535 and, for chemical sensors, is a flat representation of what the A/D converter reads. This is different for temperature, humidity and pressure sensors where the following relations need to be used to retrieve the physical value:

Temperature [C]= (sample/16384*165) – 40.0

Humidity [%RH] = (sample/16384) * 100.0

Pressure [hPa] = sample / 48.0

<u>*Get the free memory RAM size*</u>

Purpose: moving average filters and internal program use a variable amount of RAM. This command allows to read the available RAM amount.

Command: M

Parameters: None

Returns: The amount of available memory RAM in bytes in 16 bit unsigned value

Example:

Tx: {M}

Rx: {M02DB} 731 bytes available

<u>*Load Preset*</u>

Purpose: The whole configuration for each channel could be saved, as a snapshot, into an persistent internal memory. This command triggers a snapshot load for a specified channel.

Command: L

Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Returns: An acknowledge frame

Example:

Tx: {L00} Load preset for channel 0

Rx: {L00}

9.4.6 Write commands

<u>*Set the Prescaler size*</u>

Purpose: Define the time base for a channel sampler.

Command: P

Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Byte2: the time base expressed in 10 milliseconds/unit (range: 0-255. 0: the sampler takes a new sample each 10ms; 255: the sampler takes a new sample each 2.55s)

Returns: An acknowledgement frame

Example:

Tx: {P0031} Set a sample time base of 0.5s for the channel 0 (31hex is 49 decimal. This specifies a time base of 49+1 units of 10ms → 0.5s).

Rx: {P00}

<u>*Set the IIR denomitators*</u>

Purpose: Each sample is filter by two single order IIR filters where the denominator values could be set. The denominator is always a multiple of 2. This command sets the denominators for the two IIR filters.

Command: A

Parameters:

Byte1: the sensor channel ID (from 0 to 6)

Byte2: the two power factor defining the denominator of the 1st IIR filter (0 and 255 disables the filter; valid values are 1, 2, 4, 8, 16, 32, 64, 128)

Byte3: the two power factor defining the denominator for the 2nd IIR filter (0 and 255 disables the filter; valid values are 1, 2, 4, 8, 16, 32, 64, 128)

Returns: An acknowledge frame

Example:

Tx: {A000408} Set the IIR denominators for the channel 0 to, respectively, 4 and 8

Rx: {A00}

Set the decimation filter size

Purpose: each filtered sample is decimated by a decimation filter. This command sets the size of the decimation filter.
Command: D
Parameters:

Byte1: the sensor channel ID (from 0 to 6)
Byte2: the decimation filter size (from 0: filter disabled, to 255: take one sample each 255 incoming samples)

Returns: An acknowledge frame containing the sensor channel ID
Example:

Tx: {D0105} Channel 1: take one sample every 6 incoming samples
Rx: {D01}

Set the averager filter size

Purpose: Each sample extracted from the decimation filter is averaged by mean of a moving average filter. This command sets the size of the moving average window
Command: O
Parameters:

Byte1: the sensor channel ID (from 0 to 6)
Byte2: the moving average windows size, in bytes (0: disable the filter)

Returns: An acknowledge frame containing the sensor channel Id
Example:

Tx: {O023C} Set the channel 2 averager length to 60 samples
Rx: {O02}

Write Analog Front End setup

Purpose: Each chemical sensor channel is equipped by a programmable analog front end implemented by the LMP91000 integrated circuit. This command writes the internal registers for the specified channel and is used to configure the analog front end in order to adapt it to the attached sensor. Details on values to be assigned to the internal registers are reported on the device datasheet.
Command: R
Parameters:

Byte1: the chemical sensor channel ID (from 0 to 3)
Byte2: TIA register value
Byte3: REF register value
Byte4: MODE register value

Returns: An acknowledge frame containing the chemical sensor channel ID
Example:

Tx: {R001F9603} Sets the channel 0 analog front end to:
Gain: 350 kOhm
Load: 100 Ohm
Reference: External
Internal zero: 20%
Bias polarity: Positive
Bias percentage: 10%
Shorting FET: disabled
Working mode: 3-lead amp cell
Rx: {R00}

Setup reference voltages

Purpose: Each chemical sensor channel is equipped with a precise programmable three channel voltage reference generator. This command sets the generators to provide the required reference voltages.
Command: C
Parameters:

Byte1: the chemical sensor channel ID (from 0 to 3)
Byte2: the voltage reference ID to be programmed.
00: Vin- A/D input
01: Vref A/D
02: LMP91000 external VREF

Byte3-4: a value representing the voltage to be generated (range: 0-4095)
Byte5: the overall output stage multiplier
00: x1 (output voltage is 0-2.5V)
01: x2 (output voltage is 0-5V)

Returns: An acknowledge frame containing the chemical sensor channel ID

Example:

Tx: {C01000FFF00} Sets the channel 1 A/D input Vin- pin to 2.5V
Rx: {C01}

NOTE: The output multiplier is common for the three generated references this means is not possible to set up different gains for references on the same channel.

Save preset

Purpose: The whole configuration for each channel could be saved, as a snapshot, into a persistent internal memory. This command triggers a snapshot for a specified channel and associate a channel name for it. The saved preset is automatically recalled each power up or board reset.

Command: W

Parameters:

Byte1: the sensor channel ID (from 0 to 6)
Byte2-9: the sensor name (valid only for channels 0 to 3). The encoded string should be zero terminated.

Returns: An acknowledge frame containing the sensor channel ID

Example:

Tx: {W004E4F203345203100} Save the preset for channel 0, name to “NO 3E 1”
Rx: {W00}

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