Chapter 3
"The Invisible Made Visible": Science and Technology

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An Introduction by Marco van Lochem

As described in Chap. 2, it started for me in 2010. After almost 20 years working in the IT and High Tech Industry, I founded my own company (Odeon Interim Management) and was looking for a way to contribute to a sustainable society. In that period, Jean-Paul Close and I met. Based on his vision and experience regarding sustainability, we discussed how we could improve the living and working environments in cities, initially in The Netherlands, but with a global focus. Polluted air is a major health hazard in world cities and a tremendous cost for society. This was the start of AiREAS, using our network and experience to create a multidisciplinary co-operation with a human value-driven sustainable focus.

In our discussions with the municipality of Eindhoven in North Brabant, the Universities of Utrecht and Twente, ECN, Philips and Axians/Imtech ICT, we defined a first tangible goal and project contributing to the higher AiREAS purpose of healthy cities. We agreed to make visible the invisible by designing and implementing an Innovative Air Measurement Network ('Living Lab') in Eindhoven.

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To get this first project started, the commitment of individual persons from these stakeholders was key (not to mention that it would help in getting commitment from their individual organizations as well). Without this, we could not have been successful. Instead of discussing budgets and investments upfront, we started by co-creating a project plan focusing on 'what has to be done and what are the deliverables.' The next step was to specify the cost of the project. And finally, we asked who would invest and for what would they be paying. It is essential to realize that AiREAS projects are not based on traditional customer-supplier relationships, but on co-creation, mutual commitment and equality.

In this way, we managed to get an agreement on the project plan, including the (fixed) budget and finance part, without losing the entrepreneurial spirit and commitment of individual persons and their organizations. This was very important because of the result-driven characteristic of the project, including the risks. We defined milestones with deliverables and payments and assured everyone that communication and co-operation were open and based on the AiREAS values of 'respect, trust and reciprocity'.

In a relatively short time, this AiREAS co-creation project managed to deliver a world class Air Measurement Network in Eindhoven. And although money and budgets were an important aspect, the focus of participants was mainly on the committed deliverables and contribution to the higher AiREAS purpose. Everybody was aware of the fact that it was a unique initiative (still small, but with huge potential and exposure) and we managed to solve problems and manage risks along the way and within the context of the AiREAS values.

Although it was only the first AiREAS project and new initiatives have already started, with many to follow, it shows that the difference is being made by individual persons taking responsibility. I therefore want to thank everybody involved for their personal commitment to join AiREAS in this great sustainable journey.

Marco van Lochem

3.1 The ILM

This document gives a comprehensive overview of the urban ILM (Innovatief Lucht Meetsysteem, English: Innovative Air Measurement System) that has been installed in the City of Eindhoven under the AiREAS initiative. Here, the intention is to provide the necessary scientific and technical details so that a user can understand the provenance of the data outcome. The social rationale for such a system was outlined in Chap. 2 of this document. Technically, the use of modern, low-cost sensors offers the possibility of obtaining new scientific insights by measuring several air quality variables at a finer temporal and spatial resolution than previously possible. Conventional networks typically measure at only one or two locations in cities the size of Eindhoven, where the temporal resolution tends to be one sample each 24 h (or even coarser).

In brief, the ILM consists of 35 Airboxes which have been installed at various locations throughout Eindhoven. These boxes contain communication and data-logger devices, as well as sensors that measure various air quality variables (particulate matter, ultrafine particle counts, ozone, nitrogen dioxide) and meteorological variables (temperature, relative humidity). These variables are measured every 10 min. Following calibration, these are made available online in near-real time. A complete archive is also made available online.

Particulate matter (specifically PM10 and PM2.5), ozone (O_3) and nitrogen dioxide (NO_2) are the most important air quality variables to be routinely measured. Ultra-fine particles are of increasing interest, but are not routinely measured. Hence, they were included in the set of measured variables. Although the ILM is low cost compared to conventional sensors, there are still cost constraints. The budget allowed for the installation of 35 Airbox sensor units, each measuring PM and O_3. NO_2 is measured at five locations, although there is a plan to expand this to 25 locations (i.e., 20 extra sensors) during 2015. UFPs are measured at six locations.

In order to measure the air quality variables at 35 locations, affordable measurement devices were needed that could easily be located and relocated within an urban setting. As accurate sensors for ambient air were not commercially available, state of the art sensors for PM, NO_2 and O_3 were modified to comply with the required specifications.

In this survey, we first provide an overview of the variables that are measured (Sect. 3.2). The technical equipment and instrumentation are then described (Sect. 3.3), followed by a discussion of data quality (Sect. 3.4). The choice of locations for spatial sampling is discussed in Sect. 3.5, followed by a discussion of data management (Sect. 3.6). Some initial results are presented (Sect. 3.7), followed by a list of projects based on the ILM (Sect. 3.8).

Each section closes with a sub-section labelled "experiences and recommendations." This outlines our experiences to date and gives recommendations for the future. Some of these recommendations are concrete and have been agreed upon. Others recommendations still need to be finalized or further discussed.

3.2 Variables Measured

Table 3.1 shows the air quality and meteorological variables that are measured by sensors in the Airboxes. Further details about the actual instruments are given in Sect. 3.3.

3.3 Instrumentation

This section gives details of the actual instrumentation used.

Table 3.1 Table showing the variables measured by instruments in the Airboxes

Variable	Description	Instrument	No. of locations	Time interval	Units
Particulate matter (PM10)	Particulate matter less than 10 μm (PM10) in diameter	Shinyei PPD42 ECN revised	All	10 min	(Mass per volume) $\mu g\ m^{-3}$
Particulate matter (PM2.5)	Particulate matter less than 2.5 μm (PM2.5) in diameter	Shinyei PPD42 ECN revised	All	10 min	(Mass per volume) $\mu g\ m^{-3}$
Particulate matter (PM1)	Particulate matter less than 1 μm (PM1) in diameter	Shinyei PPD42 ECN revised	All	10 min	(Mass per volume) $\mu g\ m^{-3}$
Ultrafine particles (UFP)/ ultrafijnstof	Particle number concentration	Aerasense NanoMonitor PNMT 1000	6	10 min	(Particle count per volume) # cc^{-3}
Ozone (O_3)	Ozone concentration	E2V MICS 2610	All	10 min	(Mass per volume) $\mu g\ m^{-3}$
Nitrogen dioxide (NO_2)	Nitrogen dioxide concentration	Citytech Sensoric NO_2 3E50 ECN revised	5[a]	10 min	(Mass per volume) $\mu g\ m^{-3}$
Temperature	Air temperature	Sensirion SHT75	All	10 min	Degrees centigrade
Relative humidity	Relative humidity	Sensirion SHT75	All	10 min	Percentage
Date/time	Recorded as UTC/GMT. May need to be adjusted to CET/CEST for communication	SIMCom SIM908	All	10 min	Uses unix time with time zone UTC/GMT
Coordinates	GPS coordinates, longitude, latitude, altitude	SIMCom SIM908	All	10 min	Degrees, minutes seconds

[a]20 extra sensors will be added during 2015, bringing the total to 25 sensors

3.3.1 The Airbox

The Airbox was developed to serve as weatherproof housing for an array of sensors. On the lower side, well ventilated space with 3 grates is reserved for mounted sensors. A 1 mm gauze is applied to prevent insects and large particles from entering. The lockable box (brand Sarel) is made of Polyester with outer dimensions of 43 × 33 × 20 cm and designed to be attached to street light poles. It carries a battery as its power supply. The battery is recharged daily during nighttime hours. The Airbox is 12 kg and 5 W.

Photo 3.1 Airbox

The UFP sensor (AeroSense Nanomonitor) is located in a separate box. This UFP box (30 × 20 × 17 cm), also by Sarel, is made of ABS/PC and attaches easily to each Airbox (plug and play). The UFP box is supplied with its own battery, 4 W and 8 kg.

Both boxes are mounted onto street light poles, the Airbox at a height of 2.5–3 m and the UFP box between 2 and 2.5 m (an example is shown in Photo 3.1).

Both boxes are CE—EMC (Conformité Européenne—Electromagnetic Compatibility) tested and approved.

The Airbox has several interfaces that communicate with the sensors and the modem. An overview is given below.

- GPRS GSM interface for transmission of sensor data and download of firmware files;
- 10-bit and 24-bit analogue interfaces for the measurement of the battery voltage, PM sensor, ozone and NO_2 sensor;
- SPI interface for temporal data storage on a SD-card;
- I2C interface measurement of the micro controller print card temperature and storage of parameters;
- RS232 interface for debugging information;
- JTAG programmable interface for the microcontroller.

The microcontroller is the basic centre of the Airbox. It samples all sensors, does certain calculations and sends the accumulated data by GPRS and through an Imtech/Axians server towards an application on the ECN server. This application permanently saves the raw data in a database. In case of server or GPRS network outage, the accumulated data is saved on the Airbox SD-card. When the server and GPRS network is resumed, data not yet transferred is automatically sent afterwards.

3.3.2 PM (PM10, PM2.5, PM1) Sensor

The basic sensor is the Shinyei PPD42, revised by ECN for improved performance. The optical sensor consists of an IR LED and a photo-transistor detector. Flow and drying of the particles is established by an electric resistor in the sensor container. In addition, the dark current of the cell is retrieved. Results are averaged over 10 min and transmitted to the ECN server. PM10, PM2.5 and PM1 concentrations are calculated sequentially.

3.3.3 UFP Sensor

The *NanoMonitor* is a small, wall-mountable device for detecting ultrafine particles in the 10–300 nm size range. The functionality of the NanoMonitor relies on electrical charging of particles in a sampled airflow and a subsequent measurement of the particle-bound charge concentration. The sensor signal is an electrical current measured by a sensitive current meter and represents the particle charge captured per unit time in a Faraday cage. The current is derived from the total charge on all airborne particles obtained after their charging in a high-voltage corona section. To reduce signal drifts over the course of time, the device periodically performs an automatic zero-offset check (typically once every 5 min).

The NanoMonitor has its own box and can easily be attached to the Airbox and moved to another according to the plug and play concept.

3.3.4 Ozone Sensor

Ozone is measured by the E2V MICS 2610, a MO_x (metal oxide) sensor that changes conductivity characteristics through ozone adsorption. The sensor is locally heated to 350 °C, but also corrected for variations in ambient temperature. In the Airbox, three ozone sensors are implemented in order to enhance the precision and reliability of the operation. The sensors are, on a monthly basis, verified by monitors operated by the national air quality network.

3.3.5 NO_2 Sensor

The NO_2 sensor is based on the electrochemical cell Sensoric NO_2 3E50 by CityTech. In order to make the sensor applicable for ambient air, it was revised to deal with interferences by trace gasses and water vapor. A differential measurement set up with a switching valve and reagent cartridges was established in front of the detecting cell. Concentration calculations take place on the ECN server. NO_2 measurement resolution is 10 min.

3.3.6 Temperature Sensor and Relative Humidity Sensor

Temperature and RH in the AirBox sensor compartment are measured with a Sensirion SHT75. The SHT75 is a digital pin-type humidity and temperature sensor. A capacitive sensor element is used for measuring relative humidity while temperature is measured by a band-gap sensor. Due to instrumental heat generation, the temperature in the Airbox is on average 3 °C higher than the ambient air and appropriate corrections are subsequently made. T and RH can only be used for indicative purposes.

3.3.7 Electromagnetic Compatibility (EMC)

In order to obtain the CE approval, an Airbox equipped with UFP was tested (by Dare) according to the EMC (Electromagnetic Compatibility) directive. The following tests were performed:

- Conducted emission test (class A) according to EN55011 (2009) + A1 (2010)
- Radiated emission test according to the same standards

The above tests judge the EMC effect on other equipment.

The following immunity tests were performed:

- Harmonics according to EN61000-3-2 (2006) + A1 (2009) + A2 (2009)
- Flicker according to EN61000-3-3 (2008)
- Voltage dips and interruptions EN61000-4-11 (2004)

These tests judge the effect of external equipment on the Airbox and UFP.

The following tests were conducted on the Airbox controller print:

- Power supply checked with calibrated electrometer. Voltage deviation should not exceed 10 %
- SD-card checked on partition type and volume, as well as initialization ability
- Modem communication while located outdoors

Finally, the battery was tested. This showed that the battery can supply sufficient power for at least 18 h.

3.3.8 Experiences and Recommendations

Section 3.7 outlines certain results that show the functioning of the sensors within the Airbox and ILM system. However, it is too early to evaluate the long term performance of individual sensors, the Airbox or the ILM. This will be evaluated technically during the interim calibration (see Sect. 3.4.2) and at the end of the expected life of the project (5 years). It will also be evaluated through user experience.

3.4 Data Quality

There are three components to the evaluation of data quality.

(1) Regular **calibration** is the formal calibration of the ILM instruments against standard instruments, as well as the inter-calibration of the ILM instruments. This is further subdivided into initial calibration, interim calibration and preventative maintenance.
(2) **Validation** is the process of checking the data to ensure that they adhere to predefined quality standards.
(3) **Smart spatial data quality** evaluation and **online normalization** are research topics concerning the development of novel methods for low-cost sensor networks.

To date, only the initial calibration (part of 1) had been finalized and implemented whereas (2) is in progress (3) will form part of the DAMAST research project and may be a component of other future research projects.

It is important that the outcome of any data quality evaluation [whether (1), (2) or (3)] is routinely reported with the data. This is discussed in Sect. 3.6 (data management).

3.4.1 Regular Calibration and Preventative Maintenance

This section describes the basic calibration of the instruments whereby the sensors are calibrated against recognized reference instruments.

3.4.1.1 Initial Calibration

The first the set of AiREAS Airboxes were operated outdoors for extended periods of time at an ECN test site. In this phase, all sensors were compared to the median time series of each sensor type (PM, O_3, etc.) for this period. This way, for each sensor, the deviation in terms of offset and slope was calculated in comparison to the median time series.

Secondly, the correlation coefficient for each sensor (expressed as R^2) with the median time series was derived. This value was used as a criterion for proper operation of a specific sensor. In case this criterion was not met, the sensor was rejected. The criteria for PM, O_3, T, RH and UFP were 0.8, 0.9, 0.8, 0.8 and 0.95, respectively. The test was based on comparison constraints retrieved by simultaneous, co-located, outdoor operation with at a minimum of 10 Airboxes for at least three days. All sensors (PM, Ozone, UFP, RH and T) were inter-compared and normalized to the median values based on the 10-min aggregated values. The average R^2 was as follows: PM 0.89, O_3 0.97, T 0.92, RH 0.98 and UFP 0.98. These all meet the above-mentioned criteria.

Next, a subset of three Airboxes was calibrated against reference equipment at an urban background site for two weeks. The reference equipment for PM10 and PM2.5 was the Met One BAM (Beta Attenuation Monitoring) and for ozone (UV photometry Thermo).

The UFP (Nanomonitor, Aerosense) was calibrated against the GRIMM SMPS (L-DMA, CPC5410) at the ECN site. The T and RH sensors that are inside the Airbox were considered indicative.

NO_2 sensors were introduced into the AirBoxes later on. In 2015, NO_2 sensors were added to five Airboxes with a plan to introduce a further 20 sensors later in 2015. These NO_2 sensors will be calibrated against a reference NO_x monitor (chemoluminescense) in Eindhoven.

3.4.1.2 Experiences and Recommendations

A problem with the implementation of the ILM has been the lack of planning and budgeting for data quality evaluation. This is an important lesson to be learned as we go forward with the ILM and as similar networks are rolled out in other cities. Recommendations for data quality evaluation for the remainder of the ILM lifetime are set out below. These should be evaluated at the end of the ILM lifetime.

It should be noted that the data quality evaluation in low-cost sensor networks is an important research topic. Traditional approaches to calibration and validation tend to be costly. A low-cost network needs a smart, low-cost data quality evaluation protocol.

3.4.1.3 Interim Calibration

After a fixed interval, each Airbox will be removed and the sensors will be calibrated against appropriate reference sensors.

The intention is to calibrate all sensors on a regular basis with certified reference equipment. The sensors are calibrated as contained in the Airbox to avoid artifacts possibly introduced by the housing. The sensors are compared with the reference equipment while exposed to ambient air for at least 48 sequential hours. The location is by preference within the application area, in this case, in the city of Eindhoven. Reference equipment is operated under certified conditions following the issued EU directives. The RIVM LML stations are suitable for this purpose. Proposed calibration frequency is once per two years. Calibration results are used to assess sensor performance characteristics and might lead to an adjusted calibration frequency. Interim calibration of Airboxes is carried out in batches (typically 1/3 of the total number of Airboxes per batch) in order to minimize disturbance of measurement series.

UFP sensors (NanoMonitor, Aerosense) cannot be calibrated in this way, as this parameter is not measured by the LML. Therefore the UFP's will be calibrated by the manufacturer. The intended calibration frequency is once a year.

Interim calibrations should, where possible, be coincident with preventive maintenance. At such an event, calibration will be executed before and after the maintenance to cover for possible induced changes in sensor performance.

3.4.1.4 Preventative Maintenance

Individual sensors (either the whole device or individual components) have a limited lifespan. Hence, a preventative maintenance program is required. The maintenance program can be combined with interim calibrations of all other sensors, including those newly replaced.

Preventative maintenance is scheduled on a biannual basis. This frequency is based on the manufacturer information of the lifespan sensitive components in the Airbox. The most important parts to be replaced are the electrochemical NO_2 cell, the NO_2 sensor cartridges, the O_3 sensor, and the Airbox and UFP box battery. Furthermore, the PM sensor will be cleaned.

After a final functional check, the serviced Airboxes with sensors will be calibrated as set out in the previous chapter. In cases of preventive maintenance coinciding with interim calibration, the Airboxes will also be calibrated beforehand.

3.4.2 Validation

This has two forms: online and afterwards. The objective is to evaluate whether the data are valid in the sense that they match what we expect from the calibration. This is less stringent than calibration, but may identify, for example, drifts in the calibration or gross errors. Possible outcomes are (i) do nothing (the data show no problems), (ii) apply adjustments/corrections, or (iii) interim calibration. The methodology for online and afterwards validation will be based on the procedures applied by RIVM (Ministry of Health) to the LML (Landelijk Meetnet Luchtkwaliteit), the nationwide measurement network.

3.4.2.1 Online

The online validation concept consists of two steps. First is the automatic check based on the internal sensor diagnosis. This is sensor-dependent. For example the dark current measurement on the PM sensor is monitored. The next step is the test on the data consistency. Outliers are invalidated. Sudden jumps in sensitivity, negative and out-of-range values, as well as flat line evolution are detected and invalidated. Corresponding criteria are managed in the metadata database. Finally, non-sensor specific information is taken into account. For example, if an Airbox is in service, the measures will be invalidated.

Furthermore, various other processes are monitored in the Airbox, such as battery voltage, processor temperature, and modem and SD card characteristics.

3.4.2.2 Afterwards

A monthly check will be performed by a validation operator. During this manual operation, sensor values of one AirBox are compared to other neighbor stations, as well as being checked for consistency within that one Airbox. The step is important because not all error values can be detected automatically by software. Also online invalidated values are reconsidered. Furthermore in case interim calibrations have been performed the correct implementation is considered and sensor with an abnormal behavior invalidated.

3.4.3 Smart Spatial Data Quality Evaluation and Online Normalization

This has been left as a research topic. Indeed, spatial data quality is an explicit part of the DAMAST project. The idea is to develop lightweight methods that can be used for data quality evaluation, validation and online normalization. A low cost sensor network requires lightweight validation. This is an active topic of scientific research in which Hamm and Stein are active.[1] There is already much research in

[1]Zhang, Y., **N. A. S. Hamm**, N. Meratnia, **A. Stein**, M. van de Voort and P. J. M. Havinga (2012). "Statistics-based outlier detection for wireless sensor networks." International Journal of Geographical Information Science **26**(8): 1373–1392.

the context of air quality—but mainly for data having a coarse resolution in space and time. The challenge is to develop approaches for the fine temporal and spatial resolution data that the ILM delivers.

3.5 Locations and Spatial Sampling

The choice of locations for the Airboxes was the subject of extensive discussion. After developing a general set of criteria, Sandra van der Sterren (Municipality Eindhoven) prepared a selection of sites with pictures to judge the suitability. This selection was evaluated by the AiREAS team, particularly by representatives of IRAS-UU, ITC-UT and ECN. After several iterations, a final selection of 35 sites was made.

The main goal of the network is eventually to map air quality and its change over time. This means that we need to understand the link between spatial and temporal variability and local sources. In practice, this may require the consideration of different scales. This begins with generic sources (roads and industry), as well as particular sources (traffic lights, roundabouts, building works, airport). Locations where people are potentially exposed are also of interest. This includes variation within the areas where people live and work. The whole city should be addressed, not just the centre; the whole population, including the most vulnerable. Finally, the new network should be coherent with the existing network of passive NO_2 measurements.

The following starting points were identified to select the sites:

- The main criterion was to select monitoring locations that are relevant for human exposure of residents of Eindhoven. All measurements were thus at sites relevant for representing exposures near homes, schools or other buildings. For example, we did not select sites at a major roundabout that may present high concentrations, but would not represent residential exposure. We further selected sites on major streets that represented residential exposure and thus tried to avoid measuring directly at the edge of a road. We also avoided such areas as industrial sites.
- The second key criterion was that the Airboxes needed to be attached to lamp posts (which provide electricity). This clearly limited the choice of locations.
- Sampling heights were a compromise between safety (not easily reached by third persons) and the desire to represent exposures. Sampling heights between 1.5 and 4 m have often been used in previous networks and research studies. In AiREAS, all Airboxes are mounted at a height roughly between 2.5 and 3 m, the UFP boxes between 2 and 2.5 m. Especially in busy streets (close to a source), this may modestly underestimate concentrations for traffic participants.
- Measurements sites should cover background locations and busy roads in about equal proportions. Busy roads were overrepresented compared to their occurrence, because they will likely be an important source of spatial variation of air pollution.

- Measurements (especially on busy roads) should be taken at a distance from the road (i.e., not directly at the curbside).
- Measurement locations in neighbourhoods should be spread over the whole city, including some neighbourhoods on the outskirts of the city. These are quiet but also close to the motorway.
- Measurements are often made at houses and schools on busy roads (e.g., on the ring road, the inner ring road and other important roads). On these roads, measurements should be performed at their representative parts. If a significant portion of a road runs through a canyon, measurements should be performed in the canyon and not on a smaller, more open portion of the road.
- Some measurements were made at locations where there are known complaints or citizen concerns.
- Measurements should be made at the same locations as instruments from the existing municipal NO_2 network or from RIVM (Rijksinstituut for Volksgezondheid and Milieu, National Institute for Public Health and the Environment).
- Offices and hospitals are less relevant than schools and homes because they tend to have circulation systems, meaning that they are less sensitive to air quality.

Information on the current Airbox locations is given in Table 3.2. Along with details of the locations, this also states which sensors have the UFP and NO_2 sensors (Photo 3.2).

3.5.1 *Experiences and Recommendations*

At this point, it is too early to evaluate the choice of Airbox locations. We only have one full year of data and not all sensors were installed (e.g., the NO_2 sensors) or properly calibrated from the start (e.g., there were initial problems with the O_3 sensors). We expect to be able to comment further on this after the second year.

Over the course of 2015, a further 20 NO_2 sensors will be added to the network, bringing the total number of NO_2 sensors to 25. There will still only be six UFP sensors, which is why the rotation scheme (Sect. 3.5.1.1) is proposed.

3.5.1.1 UFP Rotation Scheme

UFP is only measured at six sites. Two are urban background sites and four sites are located on busy roads. The limitation to six sites arose due to the relatively high cost of the UFP sensor. This limits the information that can be obtained about the spatial distribution of UFPs throughout the city. For this reason, we intend to implement a rotation scheme in which UFP sensors are moved between locations.

Table 3.2 Locations of the airboxes at the time of first installation

Location	Postal code	X	Y	Address	Airbox no.	NO_2	UFP no.	Location-description
1	5627 TE	158608	389159	Finisterelaan 45	19	x		Edge of residentialarea, nearby A2/A50 high density traffic [about 104 m between Airbox and driving lane (wall and houses in between)]
2	5626 BN	157966	388001	Amstelstraat	17			Residentialstreet near elderly home
3	5629 NK	161214	389171	Falstaff 8	5	x		Residentialstreet, area near A2/A50 (measurement is for back ground information)
4	5628 PZ	161106	387853	Maaseikstraat 7	9	x		Along residentialstreet near a park
5	5632 DN	162548	387177	Grote Beerlaan 15	6	x		Along residentialstreet
6	5622 HV	160177	386018	Rijckwaertstraat 6	28			Along residentialstreet
7	5612 NJ	160502	384307	Lijmbeekstraat 190	2			Along residentialstreet
8	5613 EE	162421	383403	Sperwerlaan 4A	20			Along residentialstreet
9	5652 SN	158275	383875	v. Vollenhovenstraat	24			Along residentialstreet in neighborhood between speedway and motorway
10	5657 AR	157305	383585	Sliffertsestraat 12	13	x		Child care at edge of new residentialarea near A2/N2 high traffic (distance 400 m)
11	5655 JJ	158078	380509	Twickel 30	14	x		Edge of residentialarea, near A2/N2 De Hogt high density cross road [distance to N2 is 78 m, to A2 is 110 m (buildings in between)]
12	5654 DT	160191	381309	Jan Hollanderstraat 70	12	x		On residentialstreet

(continued)

Table 3.2 (continued)

Location	Postal code	X	Y	Address	Airbox no.	NO_2	UFP no.	Location-description
13	5644 HL	161702	380451	Vesaliuslaan 50	32			On residentialstreet
14	5611 HV	161675	383158	Spijndhof	30	x	3	Small square/parking area in city center with little traffic
15	5614 EP	162461	382142	St. Adrianusstraat 30	27			Along residential street near high traffic ring
16	5646 JM	163804	380995	Eij-erven 41	1			Along residential street at the edge of town, nearby small park
17	5641 PX	164504	383907	Donk 24	21	x	2	Along residential street at edge of town, near small park and school
18	5612 EJ	161212	384829	Pastoriestraat 57	34	x		Primary school De Driestam, along busy crossroad. Pastoriestraat/OL Vrouwestraat 25,000–35,000 vehicles per 24 h day average
19	X	159849	382317	v. Weberstraat-Limburglaan	4	x		Secondary schools along Ring; Christiaan Huygens College and St. Lucas. Limburglaan 32,000 vehicles average per 24 h day
20	5623 NR	161815	385212	Hudsonlaan 694 (Kennedylaan)	36	x	5	Residential apartment building along Kennedylaan/very busy road
21	5621 JC	160154	385070	Boschdijk 393	35	x		Houses along busy road near 393
22	5651 LZ	159010	383907	Noord-Brabantlaan 36	39	x		Houses along busy road, near the Evoluon, nearby RIVM-national measurement station
23	5616 JG	159478	383152	Botenlaan 135	7	x		Houses at busy road/ring
24		160818	382949	Mauritsstraat bij gemeentelijk meetstation	25	x	1	Houses along busy road/West tangent

(continued)

Table 3.2 (continued)

Location	Postal code	X	Y	Address	Airbox no.	NO_2	UFP no.	Location-description
25	5611 GD	161328	383077	Keizersgracht 28	3	x		Houses along busy road/inner ring
26	5611 DM	161588	383286	Vestdijk bij Pullman-hotel/Gedempte gracht 109	26	x		Houses along busy road/inner ring
27	5613 GC	163160	383161 (is weg)	Jeroen Boschlaan 170	23	x	4	Houses along busy road/ring
28	5644 PA	162234	381613	Leostraat 17	11	x		Houses along busy road/ring
29	5643 AJ	162517	381356	Leenderweg 259	8	x		Houses along busy road. Leenderweg outside the ring, high traffic density
30		160769	383032	Mauritsstraat bij Anna v Egmondstraat	40			Close to airbox 24
31	5504 GD	163429	384034	Hofstraat 161	22	x	6	Quite road near rail track (Eindhoven-Helmond)
32	5625 EA	160917	386622	Genovevalaan	37	x		National measurement station RIVM opposite shopping center Woensel along fairly busy road
33	5582 EJ	ca 160267	ca 378349	Vincent Cleerdinlaan, Waalre	31	x		Houses in/nearby wood bos in Waalre, quiet region, light post at end of road/beginning bicycle path
34	5651 CD	159254	384161	Beukenlaan 62	16	x		Office buildings along a busy road/ring
35	5631 BN	161896	385000	Ds. Fliednerstraat	29			Maxima Medical Centre (Eindhoven)/Hospital at certain distance from busy road/Kennedylaan

A full spreadsheet can be found as an annex to the section

X and Y indicate the easting and northing (in metres) direction according to the Rijksdriehoek (RDH) coordinate reference system. RDH is the coordinate reference system for the Netherlands

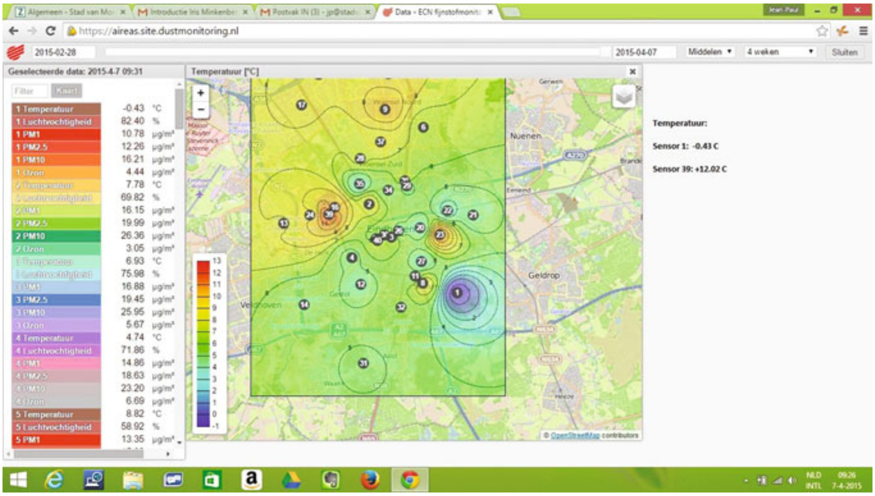

Photo 3.2 Picture of Map of Eindhoven with all ILM points

When combined with correlations with PM, NO_2 and ozone, we will then be able to build a model for the spatial distribution of UFP throughout the city. Such rotation schemes have been applied in other studies.[2,3] The rotation cycle will be completed after one year. We will then evaluate the results to determine whether the rotation scheme should be changed. This evaluation will be based on principles of spatial statistical analysis—including modelling, mapping and sampling design.[4,5,6]

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[2]Eeftens, M., M. Y. Tsai, C. Ampe, B. Anwander, R. Beelen, T. Bellander, G. Cesaroni, M. Cirach, J. Cyrys, K. de Hoogh, A. De Nazelle, F. de Vocht, C. Declercq, A. Dedele, K. Eriksen, C. Galassi, R. Grazuleviciene, G. Grivas, J. Heinrich, B. Hoffmann, M. Iakovides, A. Ineichen, K. Katsouyanni, M. Korek, U. Kramer, T. Kuhlbusch, T. Lanki, C. Madsen, K. Meliefste, A. Molter, G. Mosler, M. Nieuwenhuijsen, M. Oldenwening, A. Pennanen, N. Probst-Hensch, U. Quass, O. Raaschou-Nielsen, A. Ranzi, E. Stephanou, D. Sugiri, O. Udvardy, E. Vaskoevi, G. Weinmayr, B. Brunekreef and **G. Hoek** (2012). "Spatial variation of PM2.5, PM10, PM2.5 absorbance and PM coarse concentrations between and within 20 European study areas and the relationship with NO_2—Results of the ESCAPE project." Atmospheric Environment **62**: 303–317.

[3]**Hoek, G.**, K. Meliefste, J. Cyrys, M. Lewne, T. Bellander, M. Brauer, P. Fischer, U. Gehring, J. Heinrich, P. van Vliet and B. Brunekreef (2002). "Spatial variability of fine particle concentrations in three European areas." Atmospheric Environment **36**(25): 4077–4088.

[4]**Hamm, N. A. S.**, A. O. Finley, M. Schaap and **A. Stein** (2015). "A spatially varying coefficient model for mapping PM10 air quality at the European scale." Atmospheric Environment **102**: 393–405.

[5]**Stein, A**. and C. Ettema (2003). "An overview of spatial sampling procedures and experimental design of spatial studies for ecosystem comparisons." Agriculture Ecosystems and Environment **94** (1): 31–47.

[6]**Stein, A.** (1997). Sampling and efficient data use for characterizing polluted areas. In V. Barnett and K.F. Turkman (eds) Statistics of the Environment 3—Pollution assessment and control. Chester, Wiley.

The selected rotation scheme involves keeping one UFP sensor at a fixed location for a full year. The other five UFP sensors are kept in one location for 3.5 weeks and then moved to the next group of five locations. Thus, in 25 weeks, all 35 locations of the network can be measured once. The cycle is then repeated, meaning each site is measured for two 3.5 week periods during the year. We choose two periods in the year to avoid making comparisons between, for example, summer measurements in one group and winter measurements in another. Although rotation means that the average concentration of a site does not formally represent a true annual average, previous work has shown that, after adjustment for temporal variation, measured at a continuous reference site, spatial differences between sites can well be represented.[7]

The fixed site should be an urban background location, that will be used to correct the measurements at the other five sites for differences in time, following procedures in previous research studies (see footnote 7).[8] Each group of five being measured simultaneously should ideally represent a diversity of sites, that is, busy streets and background locations; city centre and suburban sites in different neighborhoods.

3.6 Data Management

An efficient and effective data management protocol is essential for various reasons:

- the data need to be retrieved and archived in a reliable fashion;
- various processing steps are necessary before the data can be made available to the user. These processes need to be tracked and executed;
- raw and processed data need to be archived;
- metadata need to be made available to the various users. This metadata should include the data quality information.

The main data flow is illustrated in Fig. 3.1.

The raw data is generated locally in the Airbox. The data is sent every 10 min to Axians by GPRS. Axians passes the data through to ECN. ECN performs the calculation, validation and metadata management. Metadata comes from calibration and other services. The processed data are then communicated back to Axians who make it public.

These steps are explained in more detail below.

[7]Diamond, J. (2011) *Collapse: How Societies Choose to Fail or Succeed.* Penguin Books; Revised edition.

[8]Other STIR initiatives to date are: FRE2SH (eco-city: local self-sufficiency and productivity), STIR Academy (educational triple "i" platform: inspiration, innovation, implementation) and SAFE (safety and social innovation).

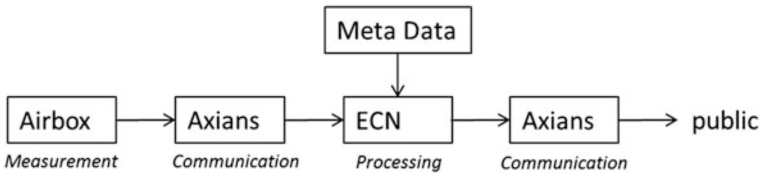

Fig. 3.1 The main data flow

3.6.1 The Airbox

At the Airbox, raw data are collected from each sensor by the microcontroller (Atmel AT90CAN128). This is done by means of 10-bit and 24-bit ADCs. In the processor, all signals are processed and averaged. (Plans are also in the works to calculate the noise level of each sensor.) A data string of 73 defined data fields is created every 10 min. Through a SPI interface, data strings are temporarily saved on an SD card. The data remains saved on the SD card until it is sent through GPRS GSM to Axians.

3.6.2 Axians (1)

Axians receives the raw data from the Airboxes and checks for a correct format. The raw data is saved in an HDF5 format. Then, this data set is forwarded directly to ECN.

3.6.3 ECN

The process is illustrated in Fig. 3.2. The Airbox data coming through Axians is collected by an Internet server and saved in a database. A direct communication line with the Airboxes makes firmware updates possible. The ECN server saves the raw data in the database.

External data is collected and saved into the database on a continuous basis. This includes, for example, information coming from the LML (Landelijk Meetnet Luchtkwaliteit (Dutch national air quality monitoring network)) stations in the region of Eindhoven.

The incoming data saved in the database are processed continuously. The raw 10-min values from the sensors are converted into concentration values using conversion formulae and constants maintained in the metadata database. The calibration parameters per sensor, also coming from the meta-database, are then applied. The processed data are then saved in the database and forwarded to Axians.

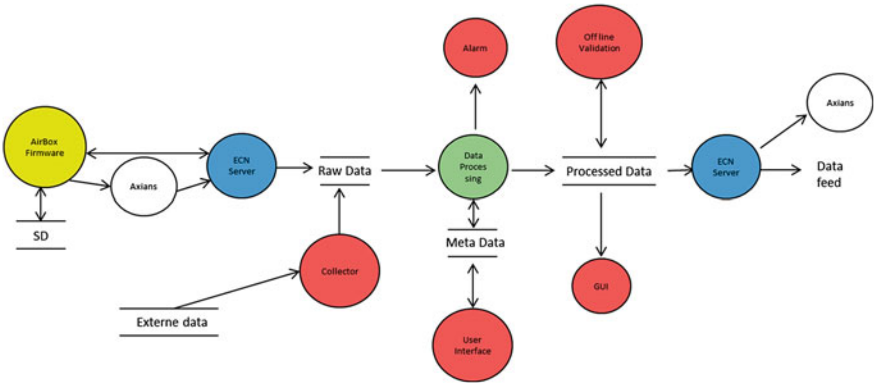

Fig. 3.2 The process at ECN

3.6.4 Axians (2)

The data are made available in three formats:

1. HDF5 (hierarchical data format version 5) files for each day. HDF is a self-describing data system which can store both data and metadata. In principle, this could contain metadata about the sensors (i.e., the lineage of the data), units and data quality information. This format (and a similar format, NetCDF) is widely used for archiving and serving environmental datasets. For example, it is used by NASA to archive and serve remotely sensed imagery. This was the rationale for Imtech (contact Carl Wolff (Axians)) to adopt this data format, and the data archive was initially only available in this format. Unfortunately, no metadata have been provided and the HDF file contains a series of tables containing the data from each sensor. A further problem in working with these data is that they do not correspond to a strict 24-h period. The data can be downloaded from: http://82.201.127.232:8080/ (accessed 28/6/15).
2. CSV (comma separated value) files for each sensor. These CSV files contain the complete dataset for each sensor since the sensor was installed (predominantly November 1, 2013). The CSV file is updated daily so that it is never more than 24 h old. The CSV files correspond to individual tables provided in each HDF file, except that they are for ALL days, not just the previous 24 h. This method for serving the archived data was introduced in autumn 2014 as an alternative to HDF. Although HDF is potentially richer in the sense that it allows more information to be archived, it has not been used to its full potential. Given the data that are provided, CSV works equally well and is more straightforward for certain users. Ease-of-use is the rationale for making the data available in this format. The data can be downloaded from: http://82.201.127.232:8080/csv/ (accessed 28/6/15).

3. Finally, the most recent data are made available in real time. For example, the most recent measurements for Airbox 1 are made available at http://82.201.127.232:3011/api?airboxid=1.cal[9] (accessed 28/6/15). The rationale for this approach is that the data are made available in real time. Using some basic software tools, a user can download these data and manipulate them in his or her own software.

3.6.5 Experiences and Recommendations

The data management and data access procedures are described above. It is highly positive that the data are freely available, although they have mainly been used by Axians (formerly Imtech), the ITC-UT and by Andre van der Wiel (Scapeler).[10] The data are content-rich and valuable from both a scientific and societal perspective. Unfortunately, various problems have been encountered when working with these data, including:

(1) The data are not easy to access. In particular, the HDF data are not easy to work with.
(2) There is a lack of metadata. This includes basic things, like the time zone.
(3) The individual tables are inconsistent. For example, the tables for Airboxes 26 and 35 have different column names than the other tables. The ordering of the tables is also different. This means that anybody wanting to work with these data must first spend time solving what should be a simple database design problem.
(4) There are several incidences of missing data.
(5) Some Airboxes have been moved since the installation of the network. Some have later been put back.
(6) At some point, there was a switch from recording floating point numbers to recording integers. According to ECN, this is because this is the limit of the precision of the instruments.

In future, the system for archiving and serving the data should address the following points.

(1) The individual tables should be consistent.
(2) Metadata should be made available with the data. This should include a basic description of the sensor, the units, time zone, etc. In the long term, the data quality information (including data quality flags) should also be provided. This should be thorough and complete.

[9]The IP address may change due to structural changes in partner relationships.
[10]Scapeler—www.scapeler.com.

(3) The data should be archived and served in a more robust and user-friendly way.
(4) We should look for alternative formats to serve the data. One suggestion has been XML (which allows the values and the metadata to be provided). An alternative could be an appropriate open-source database (e.g., PostgreSQL), together with a sensor observation service (SOS). An SOS provides an interface that allows data to be accessed directly from software over the Internet. The eventual solution will be discussed and agreed upon with the primary users.

In the future, ECN plans the following activities, which will link data management to the work on data quality.

In the coming year, an online validation procedure and an alarm function will be added to the process (see section "Online"). A further plan is to add an "afterwards" (see section "Afterwards") validation process, according to the RIVM LML validation strategy. Here, a skilled operator manually checks the dataset on a monthly basis and makes a final decision as to whether the processed values are valid or not. All data entries will be accompanied by a flag indicating the quality of the value. Based on this information, the value can be treated as fit-for-purpose or not. A GUI (Graphical User Interface) will offer users the possibility to look at all historical data in various ways.

A user-friendly interface would make input to the metadata database possible according to strict formats. The interface will also make it possible to perform queries and disclose metadata according to a user-defined structure. For now, this is a labour intensive activity.

Currently, the processed data are forwarded directly to Axians. In future, data processed according to the online validation strategy will be transmitted to Axians for display purposes only. The definitive data, validated according to the "afterwards" protocol, will be made available online.

3.7 Results

This section outlines some initial results. These link mainly to the developmental and calibration activities and to data quality checks.

3.7.1 Initial Tests of Sensors

Initially, in the summer of 2013, the Airbox sensors were tested under operational conditions. This was accomplished by comparing an individual sensor's measurement values with the average of the total set of sensors. Also, the relative sensitivity

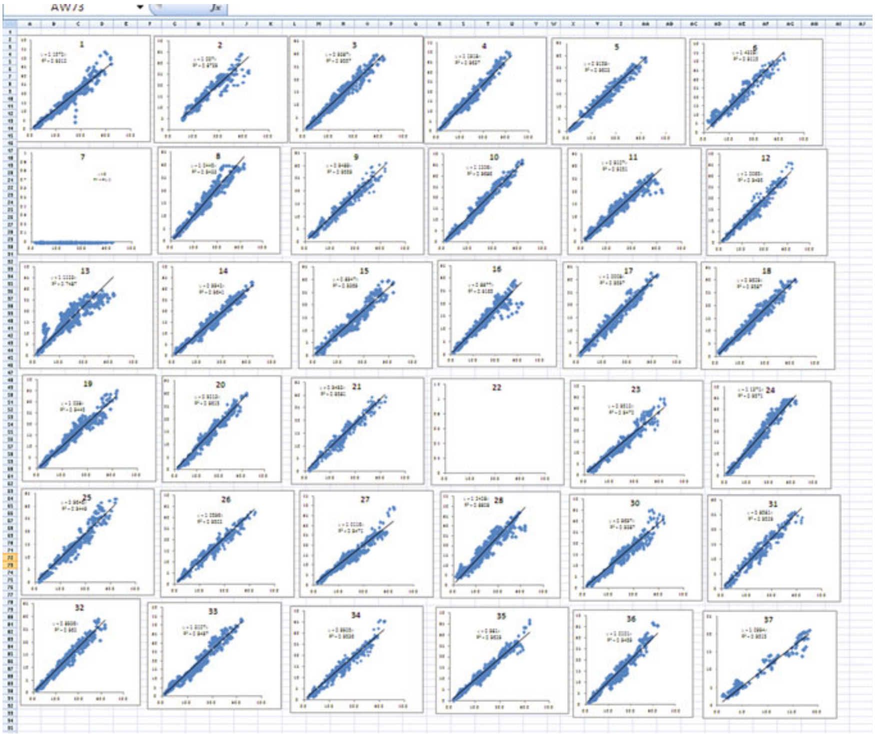

Fig. 3.3 Intercomparison PM measured per-sensor

of each sensor was determined. Figure 3.3 shows an example of the inter-comparison of one of the PM channels.

In November 2013, airboxes were operated sequentially at a reference site. The Airbox sensors for PM and ozone were calibrated against certified instrumentation. Examples are shown in Fig. 3.4.

3.7.2 Evaluation of Sensor Precision

In order to evaluate the precision of the whole sensor network, we undertook analysis during episodes of stormy weather. During such an event, the sensors are exposed to well-mixed air, and the hypothesis is that the air quality should be similar in different locations across the city. Although local effects may still be present, they will be small (relative to calm weather conditions), due to the high dilution effect. All sensors are expected to measure similar concentrations. Figure 3.5 shows an example of PM2.5 concentrations during a storm event on October 28–29, 2013.

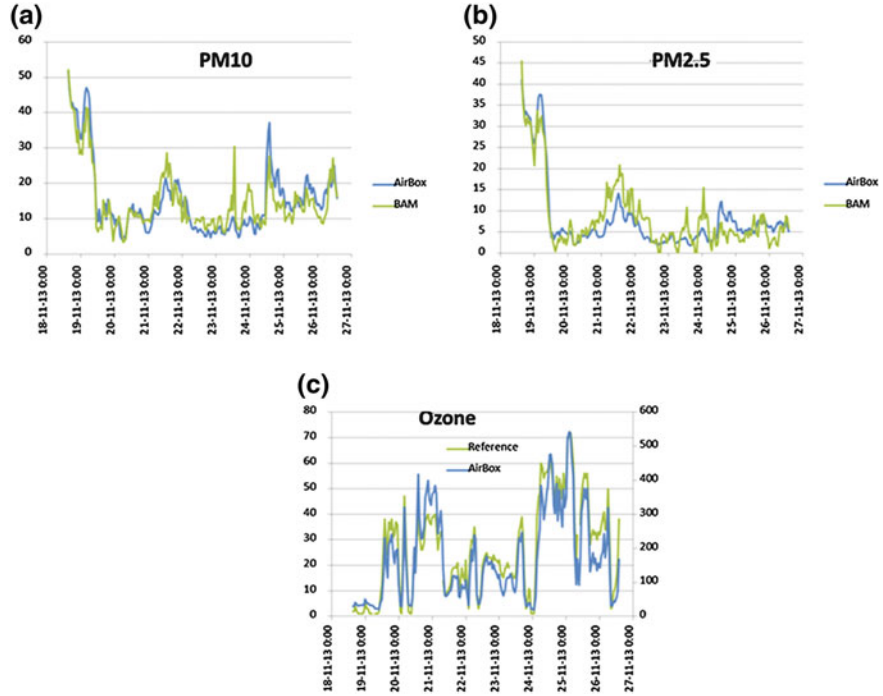

Fig. 3.4 Comparison of airbox measurements to reference measurements

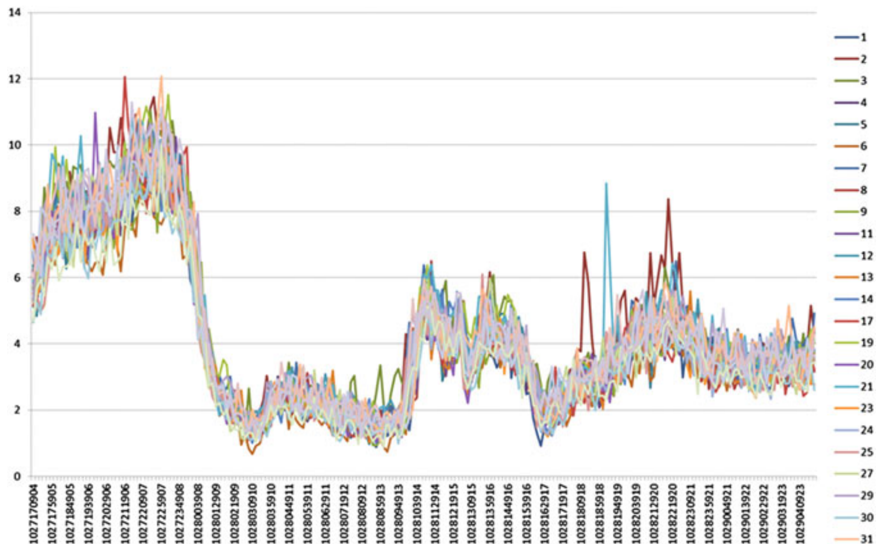

Fig. 3.5 Temporal profile of PM2.5 measurements for all sensors during the storm event of 28–29 October 2013. Units of concentration: μg m^{-3}

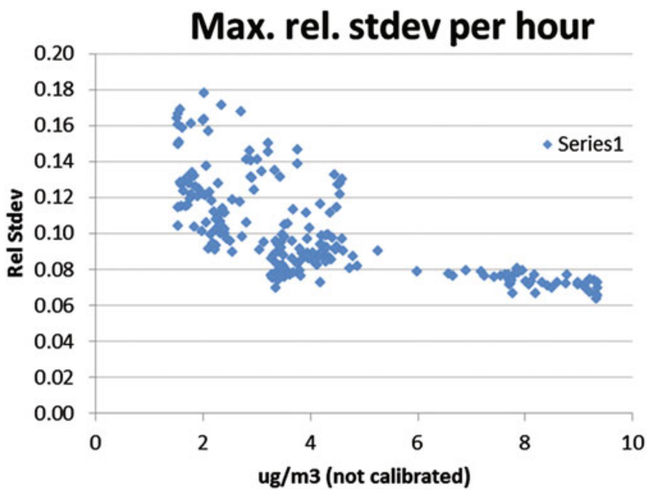

Fig. 3.6 Relative standard deviation for PM2.5 during the storm event of October 28–29, 2013

Comparing the relative standard deviation as a function of the measured concentration reveals a good precision of better than 8 % for concentrations higher than 6 µg m^{-3} (see Fig. 3.6).

The NO_2 sensors were installed in autumn 2014. A set of four sensors were co-located and evaluated at an urban background site in Eindhoven (Mauritsstraat, 2014) for a period of one week. Figure 3.7 shows the deviation of an individual sensor against the median of the others. Figure 3.8 shows the relative standard deviation of the four sensors. The relative standard deviation is of the order of 15 %, although it is higher at very low concentrations.

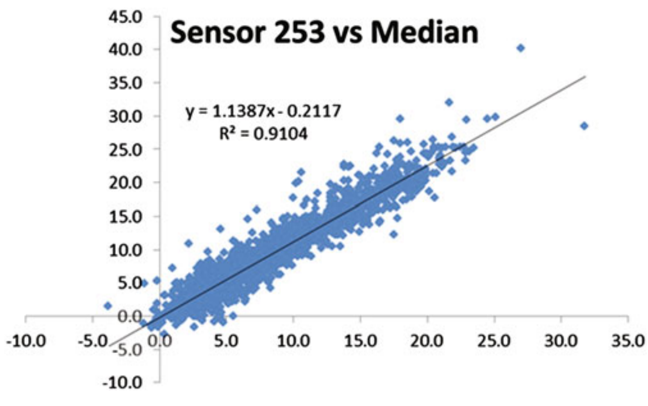

Fig. 3.7 Deviation of an individual sensor against the median of the others. Units of concentration: µg m^{-3}

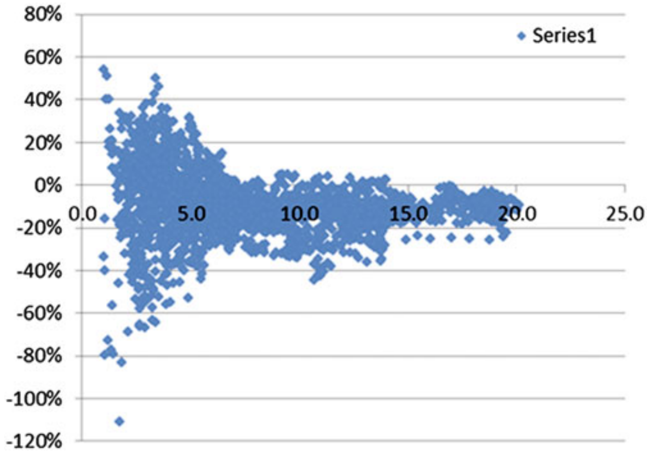

Fig. 3.8 Relative standard deviation of the four NO_2 sensors

3.8 Scientific Projects Based on the ILM

Since 2013, various projects of different size and duration have been developed based on the ILM, These all contribute to the AiREAS ideals. These are listed below.

(1) B.Sc. project of H. van Gurp

- van Gurp, H. 2014. Spatial data quality of air quality data collected at the city level. Determining the spatial data quality of the provided by the AiREAS project at the municipality of Eindhoven. Report for B.Sc. minor project, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente.
- van Gurp was one of the first users of the ILM data served by Axians (Imtech at the time). He provided useful comments on the usability of the HDF data, as well as insight into the reliability of the early ILM data, particularly the O_3 data.

(2) STW (Dutch Technological Foundation) Maps4Society call awarded the project Development of an Automatic system for Mapping Air quality risks in Space and Time (DAMAST) to ITC-UT and IRAS-UU. This will fund a promovendus (doctoral candidate) and the associated research. The doctoral candidate began on 1 September 2015.

(3) M.Sc. project of Lingyue Kong

- City-level air pollution modelling and mapping

(4) M.Sc. project of Edgardo Alfredo Vasquez Gomez (Alfredo)

- Service-based sharing and geostatistical processing of sensor data to support decision-making
- Alfredo’s thesis provides valuable insight that will help with the development of a data management framework for DAMAST and for AiREAS more generally. Alfredo is working at ITC-UT for the second half of 2015, before returning to a position in his home country of Guatemala.