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Transportable Aerosol Characterization Trailer with Trace Gas Chemistry: Design, Instruments and Verification

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ABSTRACT

The characterization of atmospheric aerosol properties and trace gas concentrations in various environments provides a basis for scientific research on the assessment of their roles in the climate system, as well as regional air quality issues. However, measurements of these face many problems in the developing world. In this study we present the design of a transportable aerosol dynamic and atmospheric research trailer, which relies minimally on the existing infrastructure by making use of wireless data transfer. The instrumentation used in this trailer was originally used in various aerosol formation studies, and has been expanded so that it can also monitor air quality. The instruments include a Differential Mobility Particle Sizer (DMPS) for aerosol number size distribution in the range 10–840 nm, a Tapered Element Oscillating Microbalance (TEOM) for aerosol mass concentration, and Air Ion Spectrometer (AIS) for atmospheric ion measurements in the size range 0.5–40 nm. Sulfur dioxide, nitrogen oxides, carbon monoxide and ozone mixing ratios are also monitored, as well as photosynthetically active radiation (PAR) and meteorological parameters. As we have already operated the trailer in South Africa for several years, we discuss the lessons learned during the first years of use in the field.

Keyword: Atmospheric aerosol particles; Atmospheric pollution; Trace gases; Climate change; Air quality.

INTRODUCTION

Trace gases and atmospheric aerosols are tightly connected with each other via physical, chemical, meteorological and biological processes occurring in the atmosphere and at the atmosphere-biosphere interface (see e.g., Seinfeld and Pandis, 1998). Human actions, such as emission policy, forest management and land use change, as well as various natural feedback mechanisms involving the biosphere and atmosphere, have substantial impacts on the complicated couplings between atmospheric aerosols, trace gases, air quality and climate (Brasseur and Roeckner, 2005; Arneth *et al.*, 2009; Raes and Seinfeld, 2009).

The need for atmospheric observations, both from the scientific and the air quality point of view is continuously increasing. For example, gas-to-particle conversion is an important source for new aerosol particles worldwide (Kulmala *et al.*, 2004; Kulmala and Kerminen, 2008). These particles also grow to climatically relevant sizes where they can act as condensation nuclei (Spracklen *et al.*, 2008; Merikanto *et al.*, 2009). Industrial countries have invested heavily on atmospheric observations and air quality monitoring during the last decades. Significant continuous monitoring operations and emission and air quality regulations have been set. In a developing world these issues are not yet at the same level (e.g., Laakso *et al.*, 2006). In a global perspective, however, there are gaps in the observations in vast areas which significant global impacts. For example, until recently, African atmosphere has not been characterized well in terms of sub-micron particle size range (Laakso *et al.*, 2008; Vakkari *et al.*, 2011; Hirsikko *et al.*, 2012).

Typically, atmospheric aerosol characterization and trace gas concentration monitoring takes place at fixed measurement sites. Due to limited resources, the number of the sites required to cover wide areas is often economically not feasible. A transportable trailer can provide a descriptive measurement data set that can be utilized in the planning of fixed measurement sites as well as a cost-effective short term solution. Another requirement for mobile monitoring arises from the need to determine the natural background conditions in aim to assess the role of different anthropogenic

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particulate and trace-gas sources in the regional context. Therefore, it is essential to conduct measurements in areas far enough from large industrial sites and cities. This is a challenging task, if the supporting infrastructure is non-existent.

The aim of this study is to present a solution to the problem described above. We constructed a robust, field-deployable suite of aerosol particle and trace gas instruments constructed onto a trailer platform that can be easily transported to those areas of interest where the supporting infrastructure is poor. The instruments were selected in such a way that the data provided by the trailer can be used to detect gas-to-particle conversion. The supporting trace gas instruments were selected so that they provide core data that can be used to generate proxy variables for sulfuric acid (Petäjä *et al.*, 2009) that are important for the new particle formation. As a side product, the trailer instruments also provide most significant air quality parameters. The instrument trailer was constructed in Finland during 2006. Prior to its shipping to a long-term monitoring mission in South Africa, a short campaign was conducted, in which the performance of the trailer instruments was evaluated against data obtained from a state-of-the-art atmospheric field station "Station for Measuring Forest Ecosystem-Atmosphere Relations", SMEAR II, in Hyytiälä, Finland. The purpose of this inter-comparison was not designed to be exhaustive, but only to illustrate that the instruments in the trailer are capable of providing long-term measurement data at a level suitable for scientific studies. Furthermore, based on the expertise gathered during the operation of the trailer in South Africa, we present a list of suggestions and improvements for a future deployment of such an instrumental setup.

DESCRIPTION OF THE TRAILER AND INSTRUMENTATION

The Measurement Trailer

The design philosophy of the trailer was to provide an infrastructure, which is transportable, easy to install, maintain and modify. The aim was to collect scientifically relevant data on the air quality parameters and only require a minimal existing infrastructure. Improvements made for the original construction based on experience gathered are discussed in Section 3.5.

A suite of aerosol and gas phase monitoring instruments were installed in a mobile, custom-made measurement trailer Eurowagon 4500 U. The trailer weighs 2500 kg and it is 4.5 m in length, 2.1 m in width and 2.3 m in height. The general layout of the hardware inside the trailer is depicted in Fig. 1. The scientific instruments are assembled in two instrument racks. They are located so that the center of mass is on the trailer axles. The side door provides access to the trailer during the maintenance visits. There is a workspace and drawers for tools, spare parts and consumables in the front of the trailer, whereas the back of the trailer can be used for storage during long-term measurements. All the pumps generate a large heat load and produce particulate matter via wear and tear of e.g., bearings as well as re-suspend dust, were placed outside of the air conditioned trailer.

The trailer was built with the idea that it would require only three-phase power and periodical maintenance at measurement sites. The maintenance routine is based on overall-checks every one to two weeks, which include cleaning the inlets, checking and replacing gas analyzer filters if needed and checking the flows of the differential mobility particle sizer (DMPS) used to measure the aerosol particle size distribution. A more thorough maintenance including calibration checks of the gas analyzers and cleaning of the instruments is needed three to four times a year in the field.

The trailer electrical system is protected against irregularities in the three-phase power from the local electricity transmission network. In the original design the incoming three phase power supply was protected from overvoltage caused by lightning with a three phase surge protector. Subsequently we installed a relay that trips if the three-phase voltage of any single phase drops under 210 V

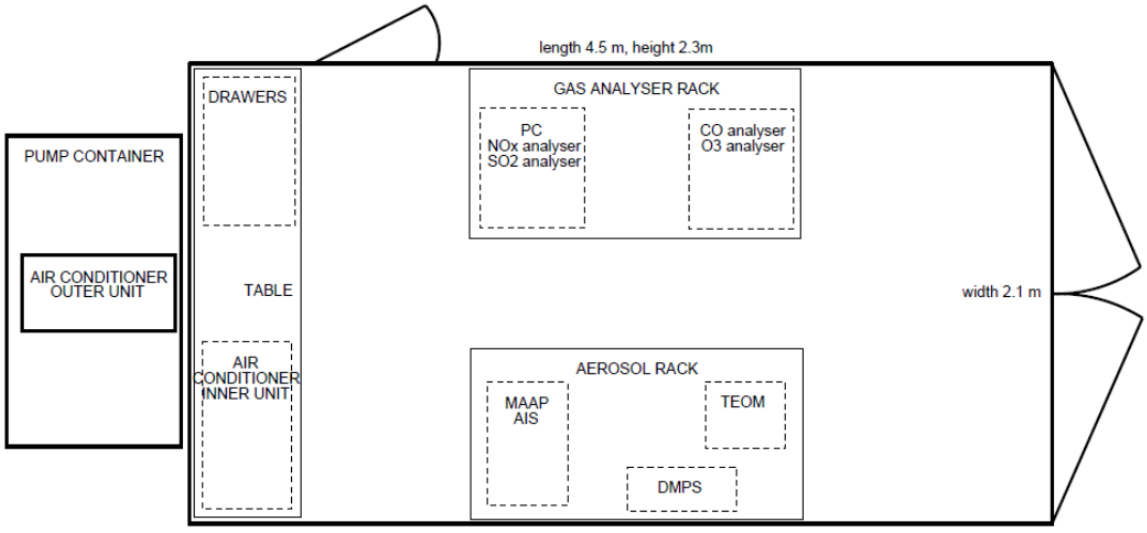

Fig. 1. A layout of the instruments in a measurement trailer.

or exceeds 240 V. This relay has also a temperature control, which automatically triggers the power off if the temperature inside the trailer exceeds a pre-selected set point. A delay circuit enables power in four minutes after the initial power outage. All the instruments are connected to surge-protected sockets, and the measurement masts and inlets are properly grounded with a sufficiently long grounding cable dug around the trailer. The measurement computer and weather station are connected through an Uninterrupted Power Supply (UPS) providing an additional protection from loss of electrical power. Additional protections added during the course of work are discussed in section 3.5.

Trailer Instruments

The trailer instrumentation includes a suite of gas analyzers measuring ozone, sulfur dioxide, nitrogen oxides and carbon monoxide and a set of aerosol particle devices monitoring number size distribution as well as mass concentration of ambient particulate matter. A general instrument layout is presented in Fig. 1 and a detailed pneumatic configuration and the sampling inlet descriptions are depicted in Fig. 2. Each instrument is separately characterized in the sections below and listed in Table 1 with relevant technical data.

Gaseous Pollutants

Several gaseous pollutants (SO_2, O_3, CO, NO and NO_x) are monitored with the trailer instrumentation. Sulfur dioxide (SO_2) is measured with a pulsed fluorescent Thermo-Electron 43S SO_2 analyzer. Since a SO_2 molecule absorbs UV-radiation, its electron configuration becomes excited and subsequently the molecule relaxes to the ground state emitting electromagnetic radiation characteristic to the energy difference between the excited and the ground state. This radiation is measured with a photomultiplier tube and the amount of radiation is descriptive for the SO_2 concentration in the air. The 43S uses a pulsed xenon lamp at 10 Hz and 130 μs time width for the pulse. The excitation light is filtered to band pass of 190–230 nm (Thermo Environmental Instruments Inc., 1992).

The ozone concentration is measured with an Environment s.a. 41M ozone analyzer based on detecting UV-light absorption by ozone. The ozone concentration is based on the difference of UV-absorption of sample air taken directly in the measurement chamber and sample taken through an ozone scrubber.

The nitrogen monoxide (NO) and nitrogen oxide (NO_x) concentrations are measured with a Teledyne 200AU NO/NO_x analyzer based on chemiluminescence of NO. The NO_x concentration is measured by directing the sample through a heated molybdenum converter, which converts NO_x to NO. The molybdenum converter, however, is not nitrogen dioxide (NO_2) specific, so some other reactive nitrogen compounds such as PAN are misinterpreted as NO_2 (Steinbecher *et al.*, 2007). In addition, some hydrocarbon compounds also exhibit chemiluminescence when exposed to ozone. In order to determine the amount of hydrocarbon interference, the instrument has a pre-reactor to mix the sample with ozone to convert all NO to NO_2 outside the reaction chamber. The pneumatic configuration of the pre-reactor allows enough time for the NO_2 molecules to relax before the measurement chamber and only the signal from possible hydrocarbon compounds is measured. This signal is then subtracted from the actual measurement. Due to these interferences, the NO_2 concentrations obtained from the trailer gas monitor needs to be regarded as an upper limit of the ambient NO_2 concentration.

The carbon monoxide (CO) concentration is measured with a Horiba APMA-360 CO analyzer based on the so-called "cross flow modulated non-dispersive infrared absorption" technique (Kato and Yoneda, 1997). In this technique, the sample and zero air flows are in alternation injected into the measurement chamber, where infrared (IR) absorption of a light source to the CO molecules is measured. The zero air is generated in the device with a burner that converts CO to carbon dioxide from the sample air. The concentration is calculated from the difference between the zero and the sample air IR-light absorption.

All the gas analyzers draw the sample through a teflon tube extending to approximately 1.5 m above the trailer roof (Fig. 2). The teflon line runs inside a steel tube, which gives enough support for the sample line. There is a steel mesh and a rain cover to prevent insects and rain water to penetrate to the gas analyzers.

Aerosol Particles and Air Ions

The aerosol particle number size distribution and total particle number concentration are measured with a Differential Mobility Particle Sizer (DMPS, Hoppel, 1978, Aalto *et al.*, 2001). The schema of the trailer DMPS is presented in Fig. 3. The instrument measures distribution from 10 to 840 nm in a 10-minute time resolution. The total particle number concentration is integrated from the corresponding number size distribution. The sample is drawn through the roof of the trailer via a Digitel DPM2.5/01/00/16 (Digitel Elektronik AG, Switzerland) inlet (Fig. 2). Prior to the sizing, the aerosol sample is dried with a Permapure MD-110-48 (Permapure LLC, USA) drier. In addition, half of the nafion drier is heated with an external heater to ensure a dry sample. This enables long-term measurements with a minimal maintenance.

The dried aerosol sample is brought to a known charge distribution (Wiedensohler, 1988) with a 370 MBq Ni-63 beta neutralizer. A medium Vienna type Differential Mobility Analyzer (DMA, Winklmayr *et al.*, 1991) classifies the particles and they are counted with a TSI model 3010 Condensation Particle Counter (CPC, Mertes *et al.*, 1995). The flows are verified with a Gillian bubble flow meter during periodic maintenance. The trailer DMPS had additional losses (e.g., drier), which lead to undersampling both in terms of concentration and size. The size distribution data presented in this study are corrected assuming a constant constant 10% under-sampling and 12% under-sizing.

The mass concentration of particles smaller than 10 μm (PM_{10}), 2.5 μm ($PM_{2.5}$) or 1 μm (PM_1) in aerodynamic diameter is monitored with a Tapered Element Oscillating Microbalance (TEOM) 1400a Ambient Particulate Monitor (Rupprecht & Patashnick Co. Inc.). A Thermo-Electron PM_{10} impactor is attached to the inlet of the TEOM. Inside the trailer there is an automatic custom made inlet switcher

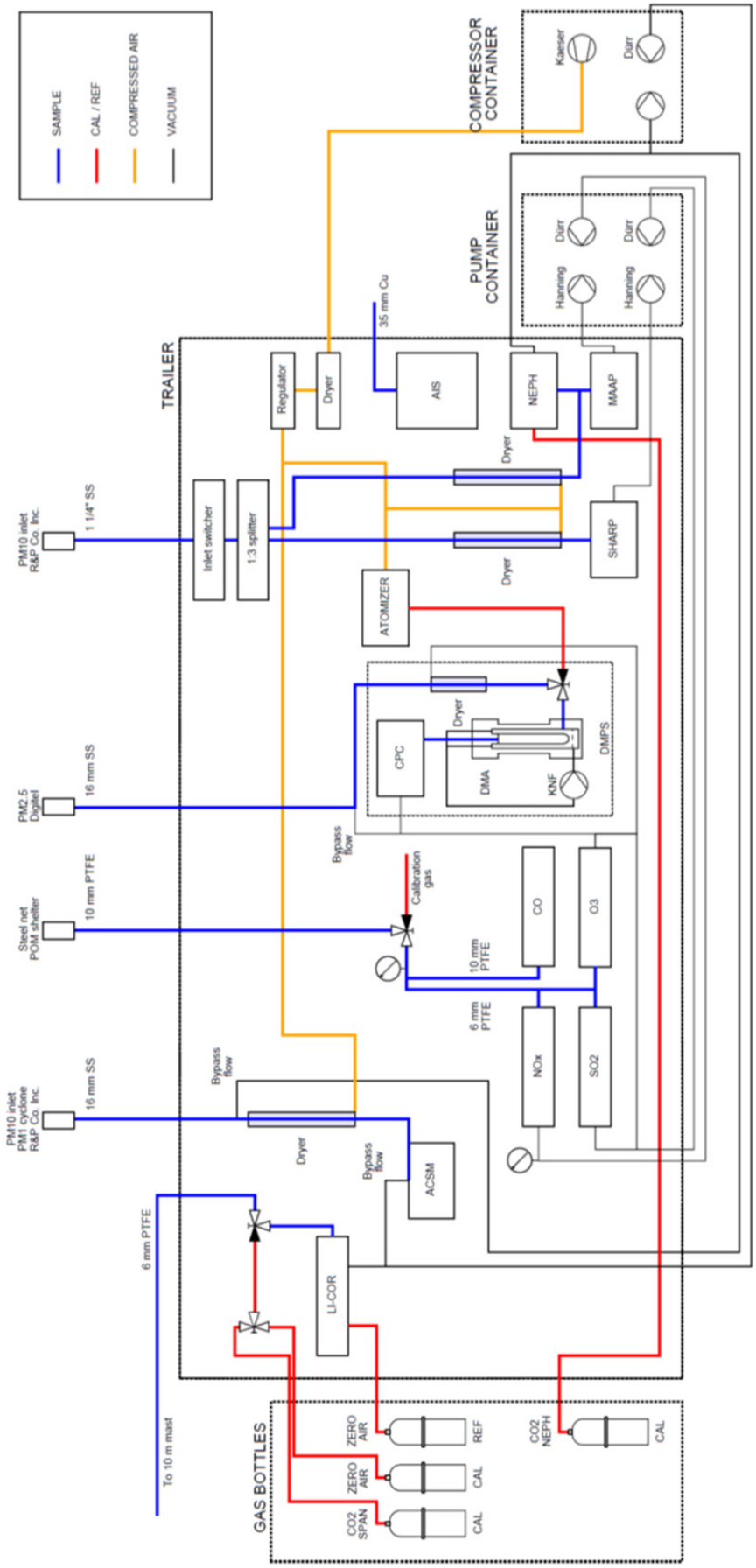

Fig. 2. Gas and particle sampling setup and pneumatic configuration of the trailer instrumentation.

Table 1. A summary of the trailer instrumentation. Acronyms in the information column indicate relevant specifications for the corresponding instruments. TR = time resolution, R = range, A = accuracy, Re = Repeatability, Th = Threshold.

Property	Instrument	Information
Meteorological parameters		TR: 10 min
Temperature	Rotronic MP 101A	R: –40 ± 60°C, A: ± 0.3°C
Relative Humidity	Rotronic MP 101A	R: 0–100%
Wind Direction	Vector A200P/L	R: 0–360°, A: ± 4°, Re ± 0.5°, Th: 0.5 m/s
Wind Speed	Vector A101ML	R: 0–75 m/s, A: 0.15 m/s (0.15–10 m/s), 1% (10–57 m/s), 2% (57–75 m/s), Th: 0.1 m/s stopping, 0.15 m/s starting
Precipitation	Thies 5.4103.20.041	R: 0–10 mm/min
Solar Radiation	LiCor LI-190SB	Photosynthetically active radiation (PAR), 400–700 nm
Aerosol particles and air ions		
Aerosol number size distribution	DMPS	R: D_p 10–840 nm TR: 10 min
Aerosol mass concentration	TEOM 1400a with a custom inlet switcher	PM_{10}, $PM_{2.5}$, PM_1 each fraction in 1 h sequentially, TR: 3 h
Air ion number size distribution	AIS	Positive and negative, R: Dp 0.4–40 nm, TR: 10 min
Gaseous pollutants		
SO_2	Thermo Environmental Instruments Inc. 43S	R: 100/200 ppb, A: 0.1 ppb
NO_x	Teledyne Instruments 200AU	R: 100/2000 ppb, A: 0.1 ppb
CO	Horiba APMA 360	R: 10 000 ppb, A: 20 ppb
O_3	Environnement S.A. O341M	R: 500 ppb, A: 1 ppb

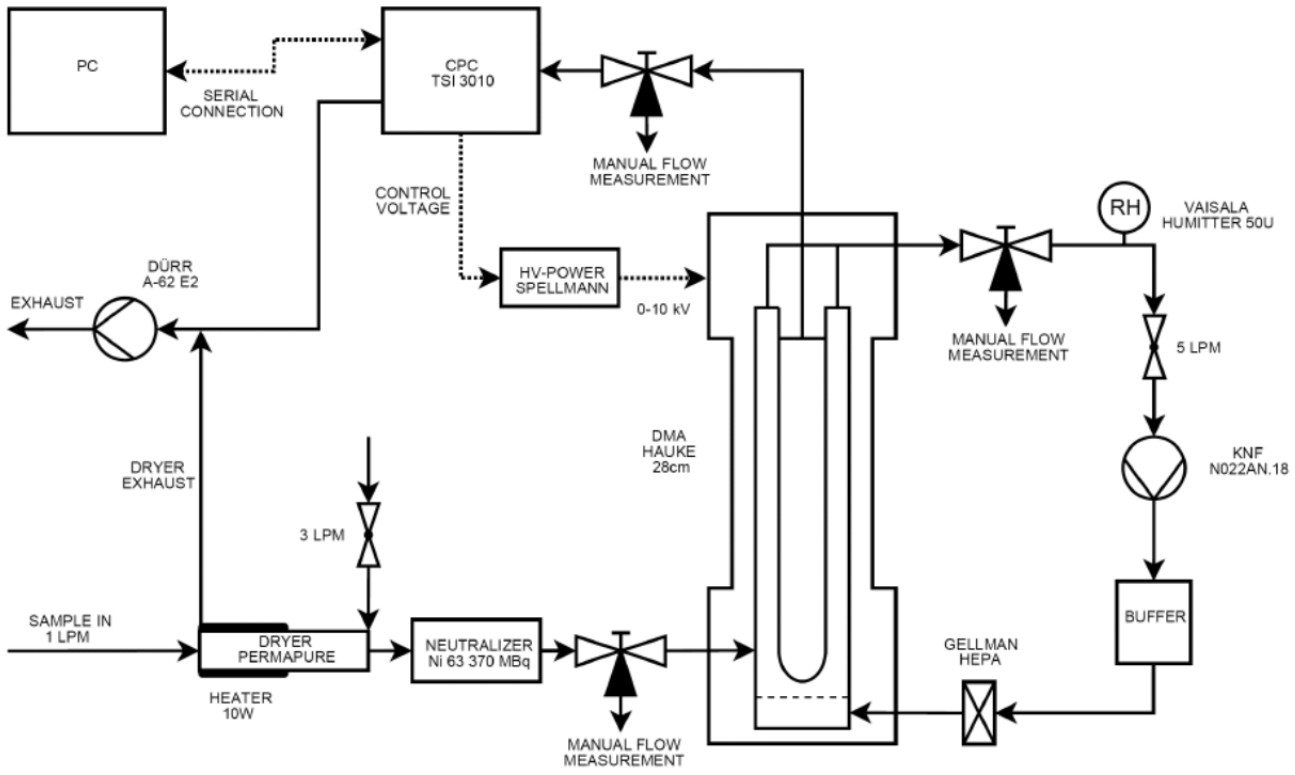

Fig. 3. A schematic figure of the trailer Differential Mobility Analyzer (DMPS) setup.

(Fig. 4) between the inlet and a TEOM. There are three options: a straight tube for PM_{10} sampling, and Thermo-Electron $PM_{2.5}$ and PM_1 cyclones for $PM_{2.5}$ and PM_1 mass sampling, respectively. A computer-controlled linear motor sequentially changes between the different mass fractions making it possible to monitor all the PM fractions with a

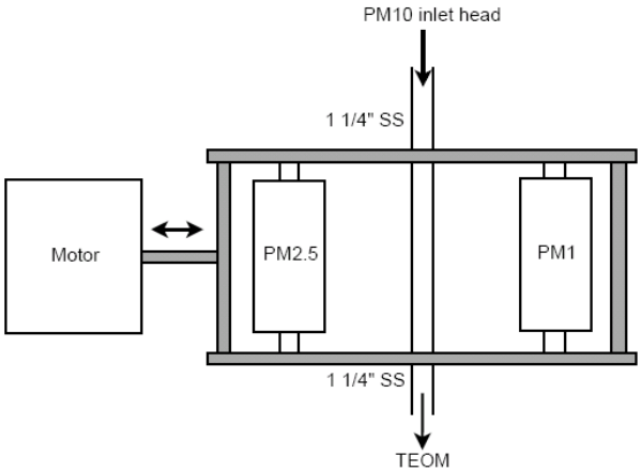

Fig. 4. A schematic figure of the trailer TEOM inlet switcher, which enables subsequent mass concentration measurements of PM_{10}, $PM_{2.5}$ and PM_1 fractions.

single TEOM unit. A pressure drop varies between the different inlet configurations and during the switching though the inlet line is never completely closed, as a result of which the mass measured by the TEOM instrument has a sudden increase as the tapered element reacts to the sudden pressure change. Thus, part of the TEOM data has to be filtered out. Nevertheless, the inlet switch enables the measurement of the PM mass concentrations in one-hour time resolution for each mass fraction, as initially envisioned by Ayers (2004) and already realized by Krieger *et al.* (2007) with two mass fractions. An additional benefit of our design is the completely vertical positioning of the inlet lines, which reduces sedimentation losses to the minimum.

Number concentrations and size distribution of positive and negative air ions are measured with an Air Ion Spectrometer (AIS, Mirme *et al.*, 2007). This instrument has two aspiration-type Differential Mobility Analyzers (DMAs), one for each polarity. The AIS classifies air ions in mobility range from 3.2 to 0.0013 $cm^2/V/s$. This corresponds to mass diameter of 0.5 to 40 nm (Hirsikko *et al.*, 2010). The air ions are detected simultaneously with 27 electrometer rings located at outer wall of the DMAs. A typical measurement cycle consists of actual measurements and an offset period of 200 s and 100 s, respectively. Air ion size distribution is thus obtained in a 5 min time resolution.

Data Transfer and Supporting Instrumentation

All the instruments in the trailer are connected to a computer, which in turn is connected to the internet via a General Packet Radio Service (GPRS) modem. Currently, the GPRS is the most commonly-used wireless data service and it is available with almost every Global System for Mobile Communications (GSM) network. In developing countries, telecommunication relies largely on mobile phone networks and new land-lines are now only rarely installed, since they need much more infrastructure. Due to the wireless data transfer the trailer does not depend on local phone lines, which can also bring in electrical spikes e.g., during thunderstorms.

Once a day measurement data are synchronized with a data already stored in a server in University of Helsinki. A compressed data file containing data for one day is approximately 350 kB in size. If the scheduled daily transfer does not succeed, a new attempt takes place in the following day. Automatic data transfer enables a remote monitoring of data quality on everyday basis from all over the world.

A weather station is located on the roof of the trailer. The temperature, relative humidity, wind speed, wind direction, precipitation rate and photosynthetically active radiation (PAR, wavelength 400–700 nm) are logged continuously in one-minute time resolution.

The trailer is equipped with a Global Position System (GPS) receiver to pin-point the measurement location. The GPS can also be used to provide a reference time for the measurements.

Verification Measurements

During the spring 2006, test measurements with the trailer setup were conducted side by side with aerosol and gas phase equipment of SMEAR II (Vesala *et al.*, 1998, Kulmala *et al.*, 2001; Hari and Kulmala, 2005) station in Hyytiälä, Finland. The tests were conducted between 29 March 2006 and 3 May 2006. The trailer was placed approximately 20 m west from the main sampling mast of the SMEAR II station.

Gaseous pollutant concentrations measured with the trailer instruments were intercompared with the corresponding SMEAR II gas measurements, which are taken from the mast at different heights. The lowest 4.2 m sampling level was used here for that purpose, but still the trailer gas sample line inlet was located deeper in the forest than this reference point and deposition to forest could be of some importance. Air ion measurements and aerosol number concentrations provided by the trailer setup were compared with the corresponding ion and aerosol particle instrumentation located in a cottage located approximately 200 m from the trailer. Data from the SMEAR II instruments were averaged to the same time resolution that the trailer devices had as indicated in Table 1.

Aerosol mass concentrations provided by the TEOM setup was compared against the masses obtained from the gravimetrical analysis of the particulate matter by a Dekati PM cascade impactor that provides PM_{10}, $PM_{2.5}$ and PM_1 fractions. Due to usually small particle mass concentrations in Hyytiälä, the time needed to collect enough material for the gravimetric analysis was three days.

RESULTS FROM VERIFICATION EXPERIMENTS

Trace Gas Mixing Ratios

The concentrations of SO_2, NO, NO_x and CO measured with the trailer instruments compared well with the measurements at the SMEAR II station. During the inter-comparison period, the trailer SO_2 concentration was within 0.2 ppb of the SMEAR II measurements, the NO concentration within 0.1 ppb, the NO_x concentration was within 1 ppb and the CO concentration was within 13 ppb. During the inter-comparison period, the mixing ratio of sulfur dioxide varied in the range 0–3 ppb, the NO varied in the range 0–0.4 ppb, and the NO_x concentration was below 5 ppb. The CO concentration was between 150 and 280 ppb and the ozone concentrations varied from 20 to 70 ppb. The overall gas phase pollutant concentrations were rather low during the inter-comparison period, which is quite typical for Hyytiälä (Luybovtseva *et al.*, 2005).

The average ratio (the slope in the regression curve) in the measured concentration between the trailer and SMEAR II gas analyzers were 0.975, 1.204, 0.866, 0.866 for SO_2, NO, NO_x and CO, respectively. The trailer O_3 analyzer, however, showed significantly lower concentrations and the corresponding slope was 0.695. To rule out the possible influence of deposition the O_3 comparison was performed also against our ozone reference instrument (Dasibi 1008-PC ozone analyzer/calibrator) connected to the same inlet line. The result of this comparison was that the trailer O_3 analyser recorded 23% smaller concentration than the reference instrument. Both the Smear II and the trailer O_3 analyzers were calibrated with the Dasibi calibrator. Sample air humidity and/or water vapour concentration was assumed to cause error in the operation of the trailer O_3 analyser, but no correlation with the observed O_3 concentration difference was found. The exact reason for the poor comparison remained unknown. In general, we may thus conclude that the mixing rations agreed within ± 25%.

The SMEAR II site is only weakly affected by anthropogenic pollution sources, which lead to low concentrations of SO_2 and NO_x. Similarly, the first campaign with the trailer in a Savannah environment revealed, on average, rather low trace gas concentrations (Laakso *et al.*, 2008). Subsequently, the trailer was deployed in more polluted locations (Vakkari *et al.*, 2010) in South Africa. In all the studies the gas analyzers were periodically checked, and adjusted if needed, against calibration gases and ozone reference instrument, as is the common practice. The fact that we were not able to verify the gas analyzers in high concentrations in ambient air during the study in Hyytiälä does not hinder the future deployments of the trailer given that the instruments are carefully calibrated and verified at the deployment site.

Aerosol Mass Concentration

Different instruments were used to measure aerosol mass concentration (PM_1, $PM_{2.5}$, and PM_{10}) in the trailer and at SMEAR II. In the trailer we had a TEOM with the custom inlet switcher and at SMEAR II a gravimetric analyses were conducted with a Dekati three-stage impactor. Typical mass concentrations were in the range 4–20 $\mu g/m^3$. Since the impactor sampling requires enough mass for gravimetric analysis, we averaged the TEOM signal to the same 2–3 day periods that were concurrent with the impactor collection times.

The mass concentration obtained with the TEOM agreed within ± 10% with the gravimetric analyses in all three mass fractions with a high linearity (Fig. 5). Already Ayers (2004) proposed the idea to use a single TEOM instrument in monitoring several mass fractions in sequence. His initial work was only a theoretical investigation that revealed negligible (0–3%) effects on 24 h average mass concentrations stemming from the slow variations in the PM mass concentrations due to time sharing. In principle, this is a cost-effective way to give added value to the air quality monitoring stations by providing a method to produce mass concentrations in several mass fractions with a single instrument. This removes the need of cross-calibrations between the instruments and the bias for all the fractions remains constant. Krieger *et al.* (2007) tested this scheme successfully in Zurich with two mass fractions (PM_{10} and PM_1) and showed a feasibility of the inlet sharing.

The pressure changes caused by the custom-made inlet switcher disturbed TEOM measurements up to 40 minutes after the inlet change. This is considerably longer than with a TEOM inlet design by Krieger *et al.* (2007), where they only had to discard the first 12 seconds of data after the inlet switch. The long integration time is problematic in an environment with fast changing mass concentrations, e.g., urban atmosphere with a lot of local close-by sources. Due to the low time resolution and a lot of required maintenance, the TEOM instrument with the inlet switcher was subsequently replaced with a SHARP 5030 mass monitor. However, if the mass concentration varies only moderately during the three-hour duty cycle, which seems to be the case in the inter-comparison measurements in Hyytiälä, our method does not suffer from the long off-line period. The comparison of three-day averages calculated from the TEOM measurements cleaned from the inlet switching disturbances showed a very good agreement with the Dekati three-stage impactor samples taken during the comparison measurement period (Fig. 6).

New Particle Formation Events

New particle formation events are frequent in Hyytiälä (e.g., Dal Maso *et al.*, 2005). Since the size range of the Twin Differential Particle Sizer (Aalto *et al.*, 2001) spans from 3 nm up to 950 nm in the SMEAR II station, it captures better the dynamical behavior of these events than the trailer instrumentation. In order to get a handle on this, the new particle formation events observed during the

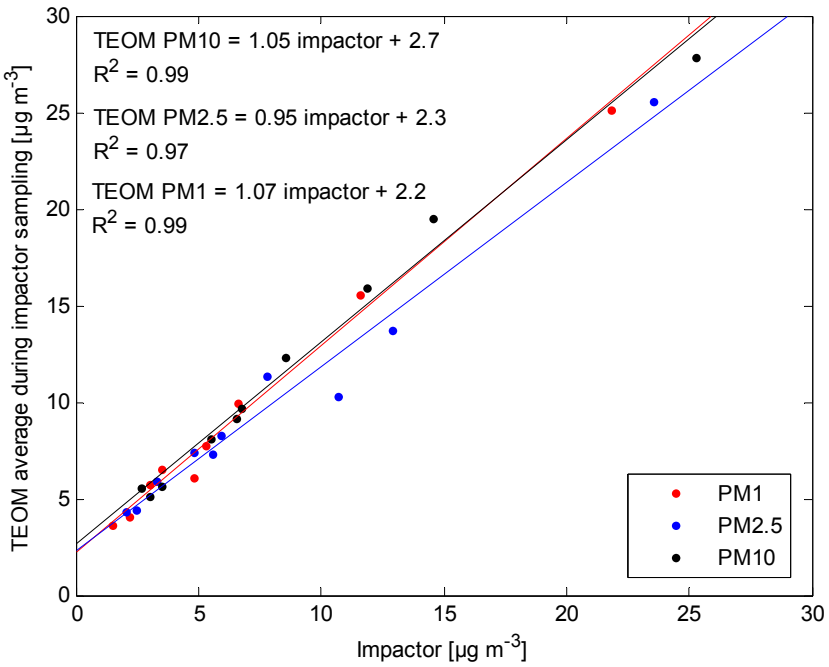

Fig. 5. Correlation of the particulate matter mass in PM_{10}, $PM_{2.5}$ and PM_1 fractions obtained with a gravimetric analysis and the trailer TEOM. For each fractions linear least squares fit with corresponding slope and offset values and the correlation coefficients are included.

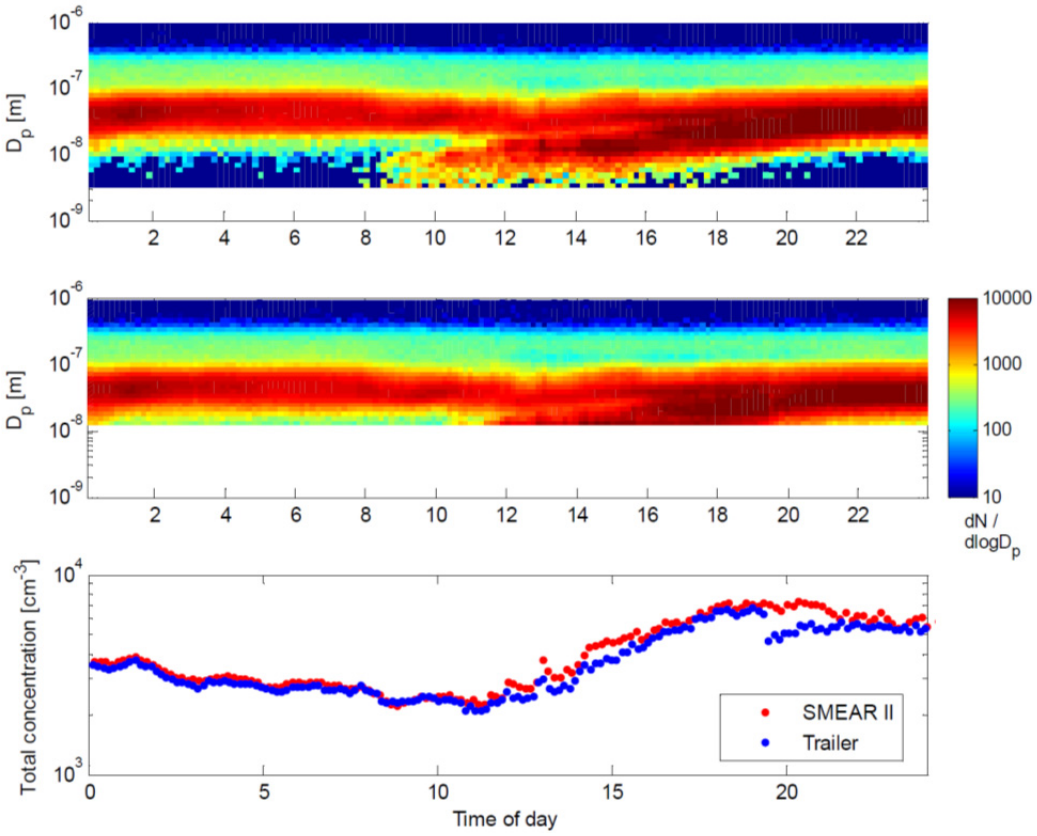

Fig. 6. Surface plot of particle number size distribution evolution during new particle formation event. Aerosol number size distribution with a) the trailer DMPS and with b) the SMEAR II DMPS as well as total number concentration determined by the two instruments during a new particle formation event day (April 22, 2006). The total number concentration is within 5% during the night. The disagreement during the day is due to the fact that the trailer DMPS is not able to detect particles below 10 nm.

comparison period were analyzed using both the trailer and SMEAR II data independently. The events were classified using the method described by Dal Maso *et al.* (2005). The particle formation rates (J) were calculated as in Kulmala *et al.* (2007), and the particle growth rates (GR) were determined using the method by Hirsikko *et al.* (2005). In the case of the trailer data, the growth rates were calculated for the size range of 10–25 nm, and formation rate was determined at 10 nm (J10). The lower cut-off size at the SMEAR II DMPS enabled determination of the GR also in the size range 3–25 nm and formation rates at both 3 and 10 nm (J3 and J10). The observed formation rates and growth rates using DMPS data are presented in Table 2 and growth rates obtained from AIS data are presented in Table 3.

Based on aerosol number size distributions, a total of eight new particle formation events were observed at the SMEAR II station during the inter-comparison period. In six of them, the trailer was able to detect the event as well. During the missing two events also the SMEAR II data did not provide growth rates and formation rates larger sizes, indicating that the events were weaker in the initial particle production and subsequent growth (type 2 events in the Dal Maso *et al.* (2005) classification scheme). The average GR based on SMEAR II and trailer data was 3.8 and 3.6 nm/h, respectively, for the particle size range of 3–25 nm. This is in agreement with previous analyses in Hyytiälä, in which the typical values of GR are from 2 to 4 nm/h (Dal Maso *et al.*, 2005; Dal Maso *et al.*, 2007) during April-May months.

The formation rate of 10 nm particles (J10) during the inter-comparison measurements varied from 0.4 to 1.6 cm^{-3}/s and from 0.2 to 2.5 cm^{-3}/s for the trailer and SMEAR II data, respectively. These are within the range of typical values during spring-time in Hyytiälä (Dal Maso *et al.*, 2005, 2007). The formation rate of 3 nm particle based on SMEAR II data was 26% higher than that of 10 nm particles, which

Table 2. Growth rates (GR) and formation rates during the intercomparison period in Hyytiälä during spring 2006. The trailer DMPS detection limit was 10 nm and thus only GR from 10 to 25 nm and formation rate at 10 nm (J10) were possible to calculate. For comparison, the similar data acquired from the SMEAR II station DMPS are presented as well as formation rate of 3 nm particles (J3) and GR between 3–25 nm particle size. On two days we were not able to determine the characteristic values with 10 nm detection limit. This is indicated with n.a. (not available). Characteristic averages are calculated only from the concurrent data.

	Trailer DMPS		SMEAR II DMPS			
Date in 2006	GR 10–25 [nm/h]	J10 [cm^{-3}/s]	GR 10–25 [nm/h]	GR 3–25 [nm/h]	J10 [cm^{-3}/s]	J3 [cm^{-3}/s]
March 27	n.a.	n.a.	n.a.	1.37	n.a.	0.824
April 16	1.95	0.419	2.17	1.82	0.735	0.935
April 17	n.a.	n.a.	n.a	1.35	n.a.	1.652
April 21	6.10	1.565	6.81	6.39	2.498	2.827
April 22	2.31	0.187	2.24	1.94	0.212	0.257
April 23	2.08	0.586	2.57	2.36	0.791	1.663
April 24	2.93	0.371	3.11	2.85	0.664	0.770
April 30	6.43	1.257	6.07	5.64	1.557	1.948
Average	**3.63**	**0.73**	**3.83**	**2.97**	**1.08**	**1.40**

Table 3. Ion formation rates and size dependent growth rates (GR) during the intercomparison period in Hyytiälä during spring 2006 for the AIS data. When the GR could not been detected, this is indicated with n.a. (not available). Characteristic averages are calculated only from the concurrent data.

Date		Trailer AIS				SMEAR II AIS			
	polarity	J_{ion}	GR 1.5-3	GR 3-7	GR 7-20	J_{ion}	GR 1.5-3	GR 3-7	GR 7-20
April 20	neg	0.05	1.5	4.9	19	0.09	1.0	4.8	25
	pos	n.a.	n.a.	8.6	24	n.a.	0.6	5.0	n.a.
April 22	neg	0.04	1.3	1.4	2.6	0.07	1.2	0.6	2.4
	pos	0.03	2.2	3.8	2.3	0.05	n.a.	3.1	2.3
April 23	neg	0.05	3.2	3.2	5.8	0.07	4.4	n.a.	4.6
	pos	0.05	2.5	n.a.	4.5	0.08	n.a.	n.a.	4.4
April 24	neg	0.11	3.7	2.7	3.9	0.11	3.9	2.8	4.0
	pos	0.07	3.0	3.2	3.5	0.09	5.1	3.5	3.9
April 25	neg	0.08	2.2	3.7	18	n.a.	1.1	4.4	n.a.
	pos	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
April 30	neg	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.9
	pos	n.a.	n.a.	n.a.	2.7	n.a.	n.a.	n.a.	1.1
average	**neg**	**0.07**	**2.38**	**3.18**	**9.86**	**0.09**	**2.32**	**3.15**	**7.38**
	pos	**0.06**	**2.57**	**5.20**	**7.40**	**0.07**	**2.85**	**3.87**	**2.93**
average	**both**	**0.06**	**2.45**	**3.94**	**8.63**	**0.08**	**2.47**	**3.46**	**5.40**

indicates competition between the growth of the freshly formed particles and their growth toward larger particle sizes (Kerminen *et al.*, 2001). On average, based on the trailer data, formation rate was 32% lower than the corresponding value obtained from the SMEAR II. This is in fair agreement, considering that the trailer was located inside the forest, whereas the SMEAR II sampled from closer to the canopy height where the losses are smaller for the freshly formed particles.

The atmospheric ion growth rates were calculated for both polarities based on trailer and SMEAR II AIS instruments for the size ranges of 1.5–3 nm, 3–7 nm and 7–20 nm (Table 3). Generally, the determined growth rates were in better agreement for the negative ions than for positive ions. In both trailer and SMEAR II, larger ions measured by the AIS tended to grow more rapidly than the smaller cluster ions, which is in agreement with previous results from Hyytiälä (Hirsikko *et al.*, 2005) and many other sites in Europe (Manninen *et al.*, 2010). The average growth rates of sub-7 nm ions concurred with previously published results (Hirsikko *et al.*, 2005). The GR of 7-20 nm positive ions seemed to be much higher for trailer than the SMEAR II data, but the mean was strongly affected by April 20 data point that was missing from the SMEAR II AIS. Given the short inter-comparison period and a spatial variability of the ion population inside the forest, the SMEAR II and trailer AIS instruments can be considered to be in a fair agreement in terms of the growth rates obtained from their data.

Aerosol Number Size Distribution and Related Parameters

When the ambient aerosol population is dominated by Aitken and accumulation mode particles, the particle number size distributions and total particle number concentration from the trailer DMPS agreed well with the state-of-the-art twin-DMPS at the SMEAR II station (Fig. 6). During a new particle formation event occurring few hours prior noon on the selected day, however, the lower detection limit of 3 nm in the twin-DMPS at SMEAR II enables the detection of new particle formation earlier than the trailer DMPS does (Fig. 7). This needs to be taken into account when extracting descriptive parameters for the new particle formation events from the trailer DMPS. To overcome this apparent imperfection related to the capability to the detection of new particle formation with the trailer instrumentation, the Air Ion Spectrometer (AIS) is included in the instrument list. The trailer AIS determined ion formation rates (Table 2) agree with the SMEAR II AIS data. Also, as seen in Fig. 7, the correlation between the number concentrations of 2–3 nm ions measured at the SMEAR II station while the trailer was deployed to Hyytiälä shows that the trailer instrumentation as a whole is sufficient for new particle formation studies during the field experiments in South Africa (Laakso *et al.*, 2008; Vakkari *et al.*, 2010).

Overall, the comparison for total number concentration, surface area, volume and condensation sink showed a fair correlation between the two instruments (Fig. 8). In terms of number, a large fraction of the particles resided in the sub-10 nm size range. This explains some of the disagreement of the two instruments in number concentration. For particles > 10 nm in diameter, the under-sampling of the trailer DMPS was 15%. The aerosol surface area and total volume obtained from the trailer DMPS were 45 to 60% lower than those obtained from the SMEAR II DMPS. The calculated total particle surface area, volume and CS were within 7%, 6% and 8%, respectively as shown in Fig. 8.

Subsequent Instrument Modifications

During the course of work, several modifications to the original instrumentation were made. As described earlier, original mass monitor (TEOM) was replaced with a SHARP 5030 mass monitor due to problems encountered with the original setup. In aim to monitor aerosol optical properties, the station was later on equipped with Ecotech Aurora 3000 nephelometer with a modified light source and inlet system (Müller *et al.*, 2010), and a Multiangle Aerosol Absorption Photometer MAAP 5012 (Petzold and Schönlinner, 2004). For accurate particle size determination without hygroscopic growth, both of these instruments as well

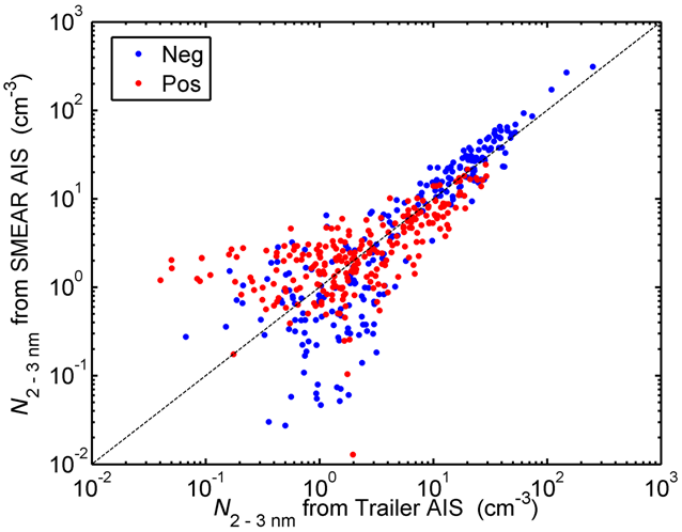

Fig. 7. Correlation of ion concentration between 2–3 nm with trailer and SMEAR II AIS's.

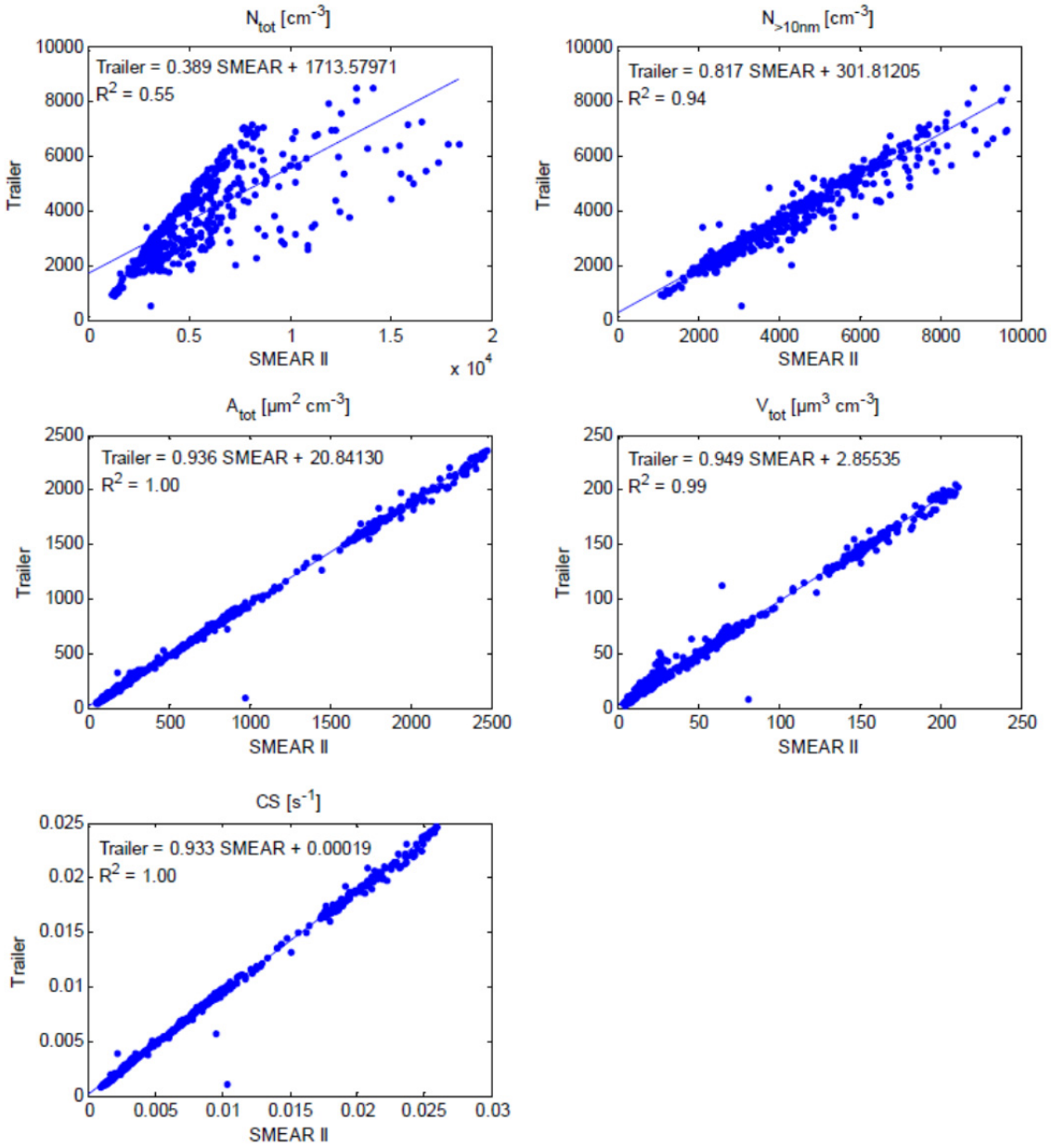

Fig. 8. Correlation of aerosol parameters obtained with the trailer DMPS and the SMEAR II DMPS, a) total particle number concentration ,b) total particle number for larger than 10 nm particles, c) total surface area, d) total volume and e) calculated dry condensation sink.

as SHARP were equipped with homemade large diameter Naphium inlet driers (see e.g., Tuch *et al.*, 2009) provided by IfT-Leipzig.

As we decided to deploy the trailer in 2010 for longer period approximately 100 km west of Johannesburg, we included new, more permanent measurements to the trailer. For ecosystem CO_2 and H_2O-flux measurements, a 10-m tall eddy-covariance mast was built (Baldocchi, 2003). Flux measurements are carried out by Licor LI7000 gas analyzer and Metek USA1 CH acoustic anemometer. The mast was also equipped with two temperature sensors (Vaisala PT100) for temperature gradient measurements. A second, 3-m tower for net (Kipp & Zonen NR lite), direct and reflected PPFD (Kipp & Zonen PAR lite) and global radiation (Kipp & Zonen CMP-3) measurements was erected. For the studies of ecosystem responses and energy balance, we also placed four temperature (Vaisala PT100) and soil moisture (DeltaT) sensors at different depths, and a Huxeflux HFP01 temperature flux probe close to the soil surface.

For shorter term case studies, we have currently (February 2011) equipped the trailer with a programmable Tenax tube sampler for several weekly samples of natural and anthropogenic VOC's, an Aerosol Chemical Speciation Monitor (Ng *et al.*, 2011) for online chemical analysis of PM_1 chemical composition, and two three-stage Dekati impactors for size-resolved particle chemical composition studies of specific compounds (e.g., levoglucosan emitted by wildfires).

LESSONS FROM THE OPERATION AT SOUTH AFRICA

The instrument trailer was shipped to South Africa after the side-by-side comparison at the SMEAR II site in June-July, 2006. It was first deployed at the Botsalano game reserve to provide data on the atmospheric and air quality parameters in a typical background conditions in South Africa. The first results are discussed in more detail by Laakso *et al.* (2008) and Vakkari *et al.* (2010), so only a summary is given here. Briefly, with the trailer instruments we were able to monitor trace gas concentrations and particulate matter in terms of mass and number at a location and biome that was not yet studied. Laakso *et al.* (2008) showed that the Botsalano game reserve was a relatively clean background site, but still affected by regional pollution sources, especially in case of sulfur dioxide and nitric oxide. The long-term measurements provided an opportunity to investigate annual cycles in a dry savannah environment. Furthermore, with the aid of the trailer, the new particle formation events were found to be very frequent and the new particle formation and growth was observed on 69% of the days and bursts of non-growing ions and sub-10 nm particles on additional 14% of the days (Vakkari *et al.*, 2010). The freshly formed particles were also seen to grow to size large enough to affect cloud formation processes. This can have implications for both precipitation patterns and even global climate (Laakso *et al.*, 2008). The trailer was later on (February 2008–May 2010) positioned on a mining-impacted area of Marikana approximately 150 km east of the first location where it facilitated a comprehensive study of local air quality (Venter *et al.*, 2012) and is currently, with updated instrumentation, permanently positioned to Welgegund background site approximately 100 km west of Johannesburg (www.welgegund.org).

Although most of the technical solutions appeared successful in a long-term operation, a daily operation of the trailer and its instrumentation has proven to be a challenging task due to continuous maintenance needed. The problems encountered can be divided into three different classes: 1) administrative and general infrastructure problems 2) Problems in technical maintenance 3) Technical changes needed for the success full operation. Each of these items is discussed in more detail in the sections below.

The general problems are related to things like access to the measurement site, safety of the location, regulation, cultural issues, responsibilities of servicing of area power lines and similar issues. These can be solved only with good local partners, but may take time. One specific concern in our case was the local traffic registration of the measurement trailer, and based on our experiences, if the site does not need to be changed very frequently, a sea container may be a good substitute for the measurement trailer (Komppula *et al.*, 2009). It provides less mobility, but is more resistant to overseas shipping, weather, unwanted human activities and can accommodate more instruments, if needed. The sea container is also easier to send around the world, as it is a known unit in the normal logistics chain. The problems related to the access to the trailer are related especially to the transportation to a remote location. In our case we solved these problems by working closely with very supportive local administrations.

At our measurement location, the data transfer suffered occasionally from the intermittent mobile network coverage. In practice this hinders the remote monitoring as the data does not transfer on a daily basis. With our trailer, when the connection is re-established, all the collected data is synchronized with the data already in the server in a larger batch, so that no data is lost in the process.

Problems in technical maintenance include both capacity building and servicing issues. As many of the instruments were new for our partners, a continuous training of the people working with the instrument was needed. This issue was pronounced by the incessant change of the people during the work which made the training of new people a necessity. Due to a limited technical expertise, the periodic major instrument service had to be done by the overseas technical personnel. The problems related to servicing were connected to the limited local service providers at the beginning of the project. All the calibration gases as well as the calibration instruments had to be imported from the outside. Another problem was the costs and delivery times of the spare parts which can be several months. Based on our experience, there has to be a local stash of spare parts and spare pumps to limit the gaps in the measurements. A close contact to local importers and service providers is also essential for the successful measurements.

Another lesson learned was the importance of the detailed instructions and technical drawings which are of high importance for the good quality measurements. An important part of the work is an electronic diary which works as a documentation of problems encountered, record for solving repeating problems and way to share relevant information. Regular cleaning helped to avoid problems arising e.g., from dust accumulation.

Mirror copies of the measurement computer hard drives were found very useful. In an unlikely, but probable computer hard disk failure during the long term measurements, the trailer instrumentation can be initiated rapidly. In our case, hard drive was replaced with a mirror copy twice. A minor, but difficult problem was faced in the form of virus-containing memory sticks. Due to limited internet connections, updating the virus databases automatically was not an option; neither was complete forbid of use of memory sticks. In our case we focused on instructing people with virus protection software as well as minimizing the evident problems taking place few times a year.

Technical changes to the original construction. During the course of the work we've found need to some changes in the original instruments and installations. These include a new air conditioning unit - another option could have been a reflecting shade on top of the trailer to reduce the incoming solar radiation.

In electrical design, the system is as vulnerable as its weakest link. During the operation of the trailer, we constructed a relay circuit protecting the trailer from under and over voltages and implemented the delay circuit to suppress the trailer instruments from turning on and off

and possibly being damaged in the process. Opto-electrical isolation and transient protection of the signal cables was proven to be important protector during frequent lightning strikes to the power lines. In addition, a lightning arrester (Phoenix Contact flashtrap compact) was added to the incoming power line approximately 10 m from the trailer to protect the system from lightning hitting the power line. On its current location, the trailer is also protected by approximately 500 m of grounding wire surrounding the site. This less mobile solution can be replaced with grounding of the trailer to e.g., a long-enough metal fences. From the crime protection point of view the fence should preferably be around the trailer. For the protection from the frequent wild fires and fire in general, the surrounding of the trailer have to be kept clean of burning material and the ground around the trailer should be covered with a material typical for the current measurement location, e.g., gravel, asphalt or cement.

CONCLUSIONS AND OUTLOOK

We have designed, constructed and tested an instrumented trailer that is relatively easily transportable to a measurement site with a minimal existing infrastructure. The trailer requires a periodic maintenance and calibration. Only three-phase electrical power is needed to initiate the measurements. The data transfer for back-up and data quality monitoring purposes is done in a wireless manner.

The trailer was constructed and its instruments were inter-compared in Hyytiälä, Finland, against a state-of-the-art field station data. Both gas phase and particulate phase pollutant parameters agreed reasonable well during the intercomparison. The instruments in the trailer were chosen based on scientific and societal outcomes and practical use. The instrument list is comprehensive enough for both air quality and scientific applications. Both gas phase and particulate phase pollutants are monitored. Both aerosol mass and number concentrations are measured, which provides key gap-filling data for monitoring the global change in the developing world (Laakso *et al.*, 2007). With the trailer we have been able to investigated background savannah environment (Laakso *et al.*, 2008; Vakkari *et al.*, 2010) and also in more polluted regions in order to obtain data for a wide range of atmospheric conditions (Laakso *et al.*, 2008b). This enables assessment of human activities on the air quality of rapidly developing Republic of South Africa. Although most of the technical solutions appeared to be successful in a long-term operation, a daily operation of the trailer and its instrumentation has proven to be a challenging task due to continuous maintenance needed (see also Scholes, 2009).

In terms of knowledge transfer and education in South Africa, the trailer provides an excellent training site for local students, technicians and scientists and provides them an opportunity to explore air quality-related projects.

From a scientific point of view, the instrumentation is suitable for many types of investigations. It has already provided a unique data set on aerosol physical character in a Savannah environment (Laakso *et al.*, 2008; Vakkari *et al.*, 2010), which can be utilized in various modeling experiments reaching across the spatial and temporal scales (Kulmala *et al.*, 2009). Furthermore, the trailer is suitable for new particle formation event (Kulmala *et al.*, 2004; Laakso *et al.*, 2008; Petäjä *et al.*, 2009; Vakkari *et al.*, 2010) studies as well as providing infrastructure and supporting data for activities such as currently ongoing aerosol mass spectrometer, ecosystem and gas-phase chemistry studies in South Africa.

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