Monitoring urban aerosol particle concentrations with the PPS-M sensor

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CONTENTS

INTRODUCTION

The most important motivation for air quality monitoring is the health effects of air pollutants and the related legislation. In Finland and other European countries the air quality standards and limits for particle concentrations in urban air are decreed by the European Union. Outdoor air quality is typically analyzed by measuring particle mass: PM10 and PM2.5 or gas concentrations: NO, NO_2, SO_2 and O_3. However, in the case of particles, it has been speculated that these mass based quantities PM10 and PM2.5 would not be the best metric to describe the health effects. The monitoring of particle surface area concentration (Oberdörster, 2001; Waters et al. 2009) has been indicated to correlate better with the effects of particulate matter than the monitoring of particulate mass concentration or number concentration. Taking the lung deposition efficiency into account, the particle surface area concentration has been proposed to be an indication of the health risks caused by particles. Thus the term lung deposited particle surface area concentration has been taken into use (Fissan et al. 2007).

There are several aerosol instruments utilizing unipolar diffusion charging. The diffusion charging is based on unipolar ions attaching on the aerosol particles.The charging efficiency, in this case the average number of elementary charges per particle, is proportional to the particle size. The larger particles gain more elementary charges than the small ones. This charging efficiency has a similar size dependency as the lung deposited particle surface area concentration. Thus after a calibration, the lung deposited surface area concentration of aerosol particles can be measured with a good accuracy by charging the particles in a diffusion charger and, after that measuring the electric charge of the particles (e.g. Fissan et al. 2007, Asbach et al. 2009).

In this study a diffusion charger based PPS-M sensor (Pegasor Oy, Tampere, Finland) was used for measuring outdoor air quality. The sensor signal was compared to the data measured by other aerosol instruments; the raw data consisting of electric currents measured from the stages of an Electrical Low Pressure Impactor (ELPI, Dekati Oy, Tampere, Finland), the particle number concentration from a Condensation Particle Counter (CPC, Model 3776 TSI Inc., Shoreview, MN, USA), the lung deposited surface area concentration measured by a Nanoparticle Surface Area Monitor (NSAM, TSI Inc., Shoreview, MN, USA) and the PM2.5 measured by two different instruments: Model 5030 SHARP (Thermo Fisher Scientific Inc.) and TEOM 1400 AB (Thermo Fisher Scientific Inc.). The PPS-M response was also compared to NO and NO_2 concentrations. Measurements were made as a part of two larger air quality research campaigns conducted in Helsinki area. The study is included in the MMEA research program of Cleen ltd, and funded by Tekes.

METHODS

PPS-M particle sensor

The PPS-M is an electrical particle sensor exploiting the unipolar diffusion charging of aerosol particles and the measurement of the electric current generated by the charged particles.. The operation principle has been introduced by Tikkanen (2009). The PPS-M can be used in several applications; although it has been designed especially for automotive exhaust particle emission measurements, also power plant emission monitoring, ambient air quality measurements as well as indoor air particle concentration measurements (Lanki et al. 2011) can be performed by the device. The use of the device in new applications may require additional components as heated sampling lines and preseparators. The operating principle of the PPS-M is illustrated in Figure 1.

The sensor has two incoming air flows: purified compressed air (1.5 bar) and the aerosol sample. The compressed air flow is introduced to a chamber including a constant electric current corona discharge. After that, the air flow carrying the positive ions generated by the corona discharge are introduced to an ejector. This air flow acts as an ejector pump drawing the aerosol sample into the sensor. The aerosol sample and the pump flow are mixed in turbulent conditions so that the ions from the corona charger can attach onto the aerosol particles included in the sample flow. After the mixing phase, remaining free ions are removed from the aerosol by an electric ion trap and the charged particles are carried out of the sensor by the gas flow. Because the particles or part of them are unipolarly charged, they are carrying electric charge out of the sensor. The PPS-M is an electrically isolated system (corona charger and ion trap) which allows charge removed by the particles to be measured by an electrometer, principle introduced by Lehtimäki (1983). The electrometer has been integrated into the PPS-M electronics. The raw signal of the PPS-M is the electric current measured by the electrometer. Basically, the signal depends on the particle concentration and size. The electronics of the PPS-M sensor allows the adjustment of the ion trap voltage, which modifies the response in smaller particle sizes. In this study, the trap voltage was set to 200 V to remove all the ions but not significantly small particles.

The maximum sampling rate of the PPS-M is 100 Hz, which is one of the highest in aerosol instruments in the market. Basically, the high sampling rate and time resolution are needed in applications as engine emission studies, where the particle concentrations and characteristics can undergo rapid changes due to the transients in driving. In outdoor measurements even the time resolution of 1 Hz is high when compared to other generally used instruments. Usually the time scale of the atmospheric aerosol processes is longer than e.g. in exhaust applications. In this study, sampling rate of 1 Hz was used, which is the same as the sampling rate of the ELPI, CPC and the NSAM.

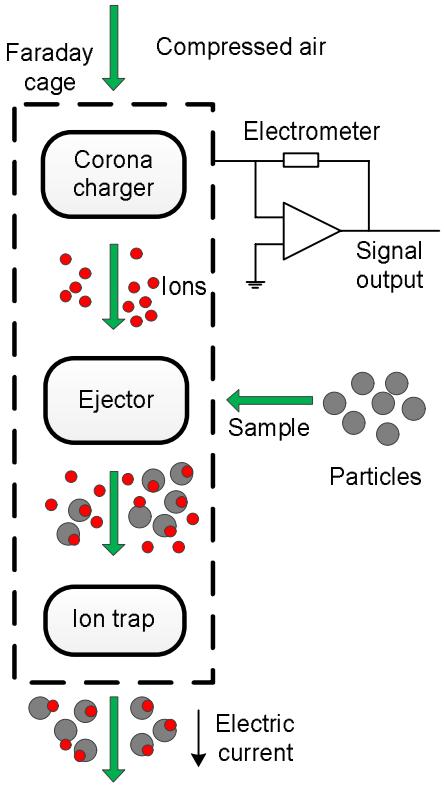

Figure 1 *The operating principle of the PPS-M*

Reference instruments

The Electrical Low Pressure Impactor (ELPI) consists of a corona charger and typically a cascade impactor with 13 different stages. 12 of stages are connected to electrometers in order to measure the electric current carried by particles. The function and structure of ELPI has been described Keskinen et al. (1992). Compared to original device, in this study the ELPI was modified in order to enhance nanoparticle resolution; we used filter stage developed by Marjamäki et al. (2002) and an additional impactor stage developed by Yli-Ojanperä et al. (2010). The collection plates of the impactor stages were equipped with aluminum foils with a thin layer of Apiezon L vacuum grease in order to prevent bouncing of the collected particles.

The Nanoparticle Surface Area Monitor (NSAM) is an electrical particle sensor featuring a rather similar principle of function as in the PPS-M (mixing type diffusion charger). Compared to the PPS-M, the main differences are the ejector construction of the PPS-M and the measurement principle of electric current; the NSAM is equipped with a Faraday cup filter which provides the electric current from the particles collected onto the filter. Also, the NSAM is designed to measure the lung deposited particle surface area concentration which is calculated from the electric current (Fissan et al. 2007, Asbach et al. 2009). The NSAM has two basic operation modes: an alveolar deposition and tracheobronchial deposition. These modes are achieved by adjusting the ion trap voltage which is 200 V for the alveolar and 100 V for the tracheobronchial deposition. In this study the NSAM was used in the alveolar deposition mode with a standard 1 µm pre-cut cyclone.

Condensation particle counter (CPC, Model 3776, TSI Inc.) was used to measure particle number concentration. According to manufacturer, the CPC had a lowest detectable particle size of 2.5 nm, 50 % counting efficiency for silver particles 3.3 nm in diameter and for sodium chloride particles or 4.1 nm in diameter (Hermann et al. 2007), and the highest measurable particle concentration of 300 000 1/cm^3.

PM2.5 was measured using Model 5030 SHARP (Thermo Fisher Scientific Inc.) and TEOM 1400 AB (Thermo Fisher Scientific Inc.) instruments. The operation of the SHARP (Synchronized Hybrid Ambient Real-time Particulate Monitor) monitor is based on the combination of β-attenuation and optical detection by light scattering. The TEOM (Tapered Element Oscillating Microbalance) utilizes oscillating filter for which the particles are collected. The frequency of oscillation is depends on the mass of particulate matter collected.

NO_x concentrations were measured by APNA 360 analyzer (Horiba Ltd.). The instrument utilizes chemiluminescence measurement principle.

Measurement campaigns

The PPS-M was tested in three different environments, all located in Helsinki area. Measurements were a part of large measurement campaigns of the MMEA research project. The focus of all the measurement campaigns was the air quality and different aspects in its monitoring. The measurement environments and focuses of the measurements were:

1. Stationary air quality measurement station in Kattilalaakso (residential area), focus on the effects of small scale domestic combustion (sauna stoves, heating) on air quality
2. Stationary air quality measurement station in Malmi (Kehä I), focus on the effects of traffic on air quality
3. Mobile laboratory in traffic (Helsinki city center and main roads nearby), focus on emissions of traffic

Two individual PPS-M sensors were used in the measurements because the stationary air quality measurements in Kattilalaakso and the measurements by the mobile laboratory were performed simultaneously during the same campaign. The locations of the stationary measurements are shown in Figures 2-4.

Stationary measurements

The first PPS-M continuous measurement was conducted in Kattilalaakso, Espoo, about 16 km west of Helsinki city center. The site and the surrounding area are shown in Figure 3. The measurement site represents a typical Finnish small-house residential area including small roads with light traffic. Kattilaaksonkatu is situated 70 m north and Nöykkiönkatu 300 m east of the site. The reported

traffic in 2012 was 3400 vehicles in workday for Kattilaaksonkatu and 10200 for Nöykkiönkatu. The nearest main road was located at the distance of 1.3 km from the site. The measurement period was scheduled from February 16th to 29th in 2012. The station was equipped with various aerosol instruments. The temperature of the camper remained rather stable, approximately 15 ºC. The sample was taken from the roof of the station without pre-conditioning like pre-separation, heating or drying. Outdoor conditions were typical Finnish winter conditions. Temperature varied between -8 and +3 ºC (weather data from Pasila) and during some days (February 19th and 23rd) there was significant snowfall.

The PPS-M was installed inside the station. The station was equipped with a supply of compressed air which was filtered using high efficiency particle filters and active charcoal filters. The excess water vapor of compressed air was removed using a membrane drier. The ELPI was used as a basic reference for the PPS-M in this measurement, but also PM2.5 measurements using a Model 5030 SHARP monitor and gas measurements, NO and NO_2 were conducted in the measurement station.

The second stationary measurement was conducted in Malmi area in order to study effects of traffic on air quality. The measurement site located approximately at the distance of 5 m from the Kehä 1 road which is one of the main roads in Helsinki area. The traffic in 2012 was in average 69200 vehicles in workday. The map of the site is shown in Figure 4. The measurement station was basically similar to the one used in the Kattilalaakso site, in spite of some differences in instrumentation. The measurement was conducted between October 19th and November 7th in 2012. The PPS-M was installed as in Kattilalaakso site. Due to the versatile instrumentation in the measurements in Malmi also the NSAM and a CPC were used as a reference instrument for the PPS-M, in addition to the ELPI, PM2.5 (TEOM 1400AB) and NO_x instrumentation.

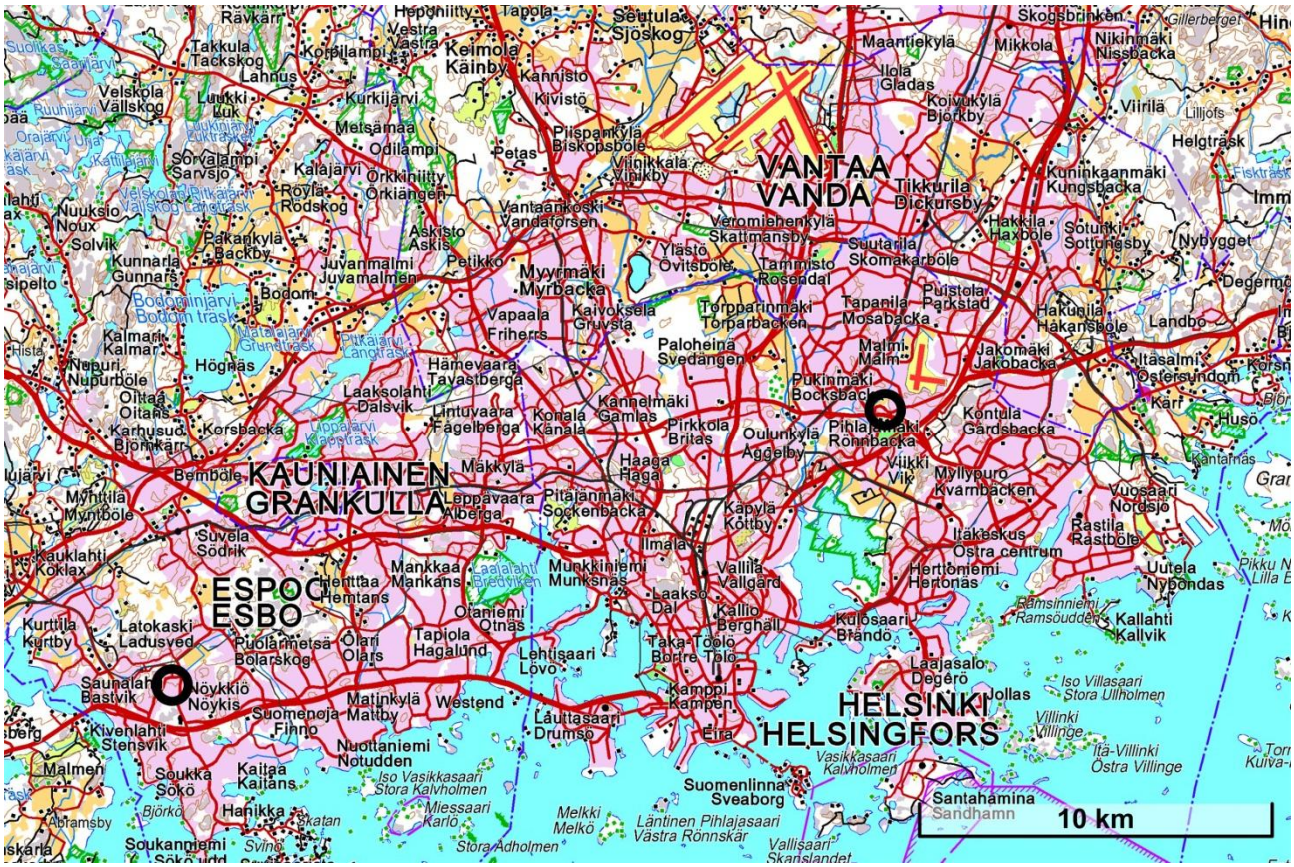

Figure 2 *Stationary measurement sites in Helsinki area: Kattilalaakso (left), Malmi (right). The map is supplied by the National Land Survey of Finland.*

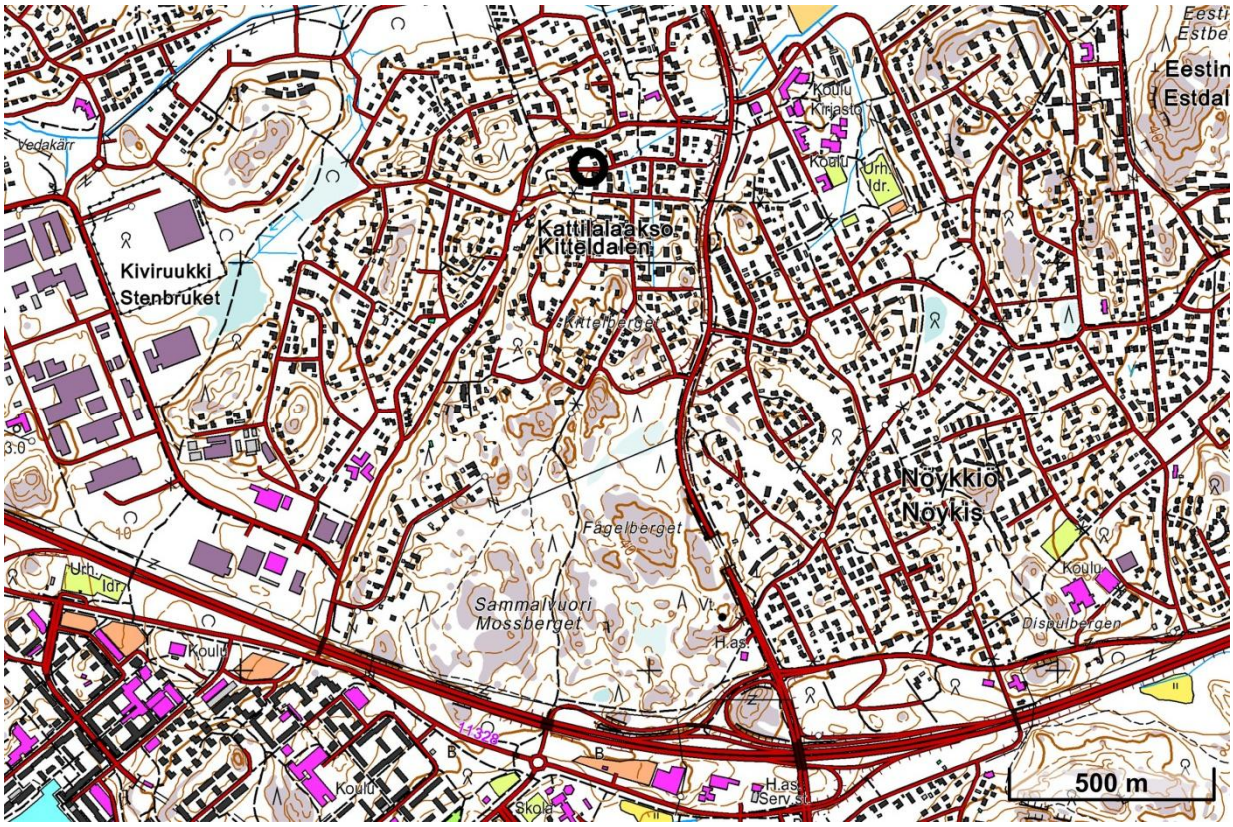

Figure 3 *The location of thte measurement site in Kattilalaakso. The map is supplied by the National Land Survey of Finland.*

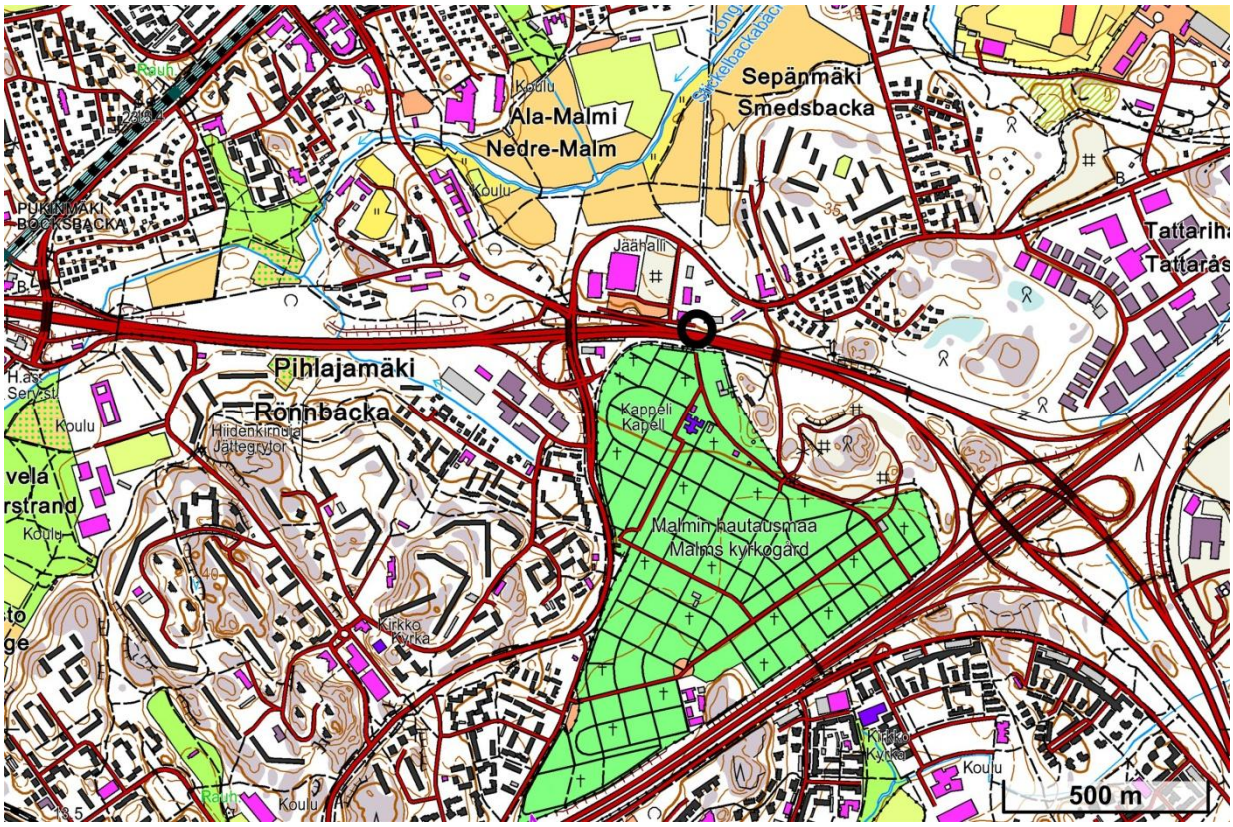

Figure 4 *The location of the measurement site in Malmi. The map is supplied by the National Land Survey of Finland.*

Measurements by the PPS-M installed into the mobile laboratory

Simultaneously with the stationary measurements in Kattilalaakso the second PPS-M was used onboard in the mobile laboratory Sniffer (Pirjola et al. 2004). In addition to the PPS-M, the mobile laboratory was equipped with various aerosol and gas sensing instruments. Compressed air required to the operation of the PPS-M was provided by using a small transportable compressor and air filtration unit. The NSAM was used as a reference for the PPS-M. The NSAM was used in the alveolar deposition mode. Before the actual measurements the electrometer of the NSAM was zeroed. Both the PPS-M and the NSAM were sampling from the same inlet tube without heating. The PPS-M was operated without pre-separation while the NSAM was equipped with a standard 1 µm inlet cyclone.

The measurement was prepared on February 15th 2012 from 16:00 to 17:00 including instrument zeroing at 16:30. The vehicle measurement started at 17:00. This time was chosen because of the heavy traffic. The first part of the measurement included the driving in Helsinki city center while the other part consisted of driving on the main commuter road in the eastern part of the Helsinki. The PPS-M measurement was stopped at 17:50.

RESULTS

Stationary measurements in Kattilalaakso

Figure 5 shows the time series of stationary measurements conducted by the PPS-M and other instruments (total current by the ELPI, PM2.5 and NOx). In Figure 6 the PPS-M data is compared to the reference instruments. Based on the PM2.5 concentrations the measurement can be divided into two different periods. Firstly, from the beginning of measurement campaign to the February 20th, the PM2.5 concentration was relatively high, ranging from 10 to 60 µg/m^3. Based on the data from other measurement stations of HSY this high PM2.5 concentration was caused by the long-range transportation of aerosol particles. Secondly, during the other period from 20th to 26th February the PM2.5 concentration was low, most of the time approximately 5 µg/m^3. The change in PM2.5 existed because of changes in origin of air masses. However, there is an increase in PM2.5 in the between February 25th (Saturday) and 26th (Sunday), probably caused by wood combustion in areas near the measurement station (heating of sauna stoves).

In Figure 5, noticeable peaks in the NO and NO_2 concentrations can be observed from the February 20th onward. The February 20th is Monday. In closer look, it can be noticed that NOx concentrations were changing in diurnal cycle so that the concentrations are increasing in the morning are decreasing around midnight. Results indicates that NO and NO_2 emissions are originated from traffic.

In summary, the measurement campaign consisted of two different periods with different origin of aerosol. Thus also the characteristics of the aerosol were different, which can be seen e.g. in the particle size distributions (Figure 7). As presented above, the PPS-M sensor has a different measurement principle compared to PM2.5; because the function of the PPS-M is based on the diffusion charging of particles, the raw signal PPS-M measurement signal is more weighted towards smaller particle sizes compared to PM2.5. As a result of this difference there are significant differences between PPS-M and PM2.5 data. This can be noticed from Figures 5 and 6. In Figure 6 the data is presented separately according to the periods (high and low background aerosol concentrations). In addition, Figure 6 shows linear fittings to the data points and values for slopes. These slopes were 7.0 fA/(µg/cm^3) during high and 13.1 fA/(µg/cm^3) during low background period. Thus, results indicate that the characteristics of aerosol affect the correlation between PPS-M raw signal and particulate mass concentration. However, when the periods were analyzed separately, the PPS-M data was observed to correlate with PM2.5. Also, it is obvious that PPS-M provides reasonable signal also for low PM2.5 concentrations.

When the PPS-M data was compared to the NOx, the behavior similar to the PM2.5 was observed; the data can be divided into the two periods with different correlations and slopes. During the latest period of the measurement campaign NOx peaked several times, due to the effect of traffic as presented above. During these peaks also the PPS-M signal was high but PM2.5 remained low. The difference between PPS-M signal and PM2.5 comes mainly from the fact that the particulate emissions of traffic are typically dominated by smaller particles as long range transported aerosol.

Because the PPS-M measurement is more sensitive on small particles than PM2.5 measurement, it follows more closely NOx concentrations.

The ELPI utilizes basically similar corona charging and electrical measurement of particles as the PPS-M. Thus, the ELPI total current provides similar information on aerosol as the PPS-M (lung deposited surface area concentration). However, the cascade impactor also allows rapid measurement of particle size distribution and particle number concentration. In order to measure comparable signal to the PPS-M only the total electric current measured by ELPI was used for comparison (Figures 5 and 6). In general, PPS-M raw data signal is 0.27 times the ELPI total current which is a result of the lower sample flow of the PPS-M (6 l/min vs. 10 l/min) and different charger construction. In our measurement we observed also a minor offset current of 17 fA. However, the correlation between the raw data measured by the ELPI and by the PPS-M was clear and always the same (slope 0.27), regardless of the differences in aerosol sample.

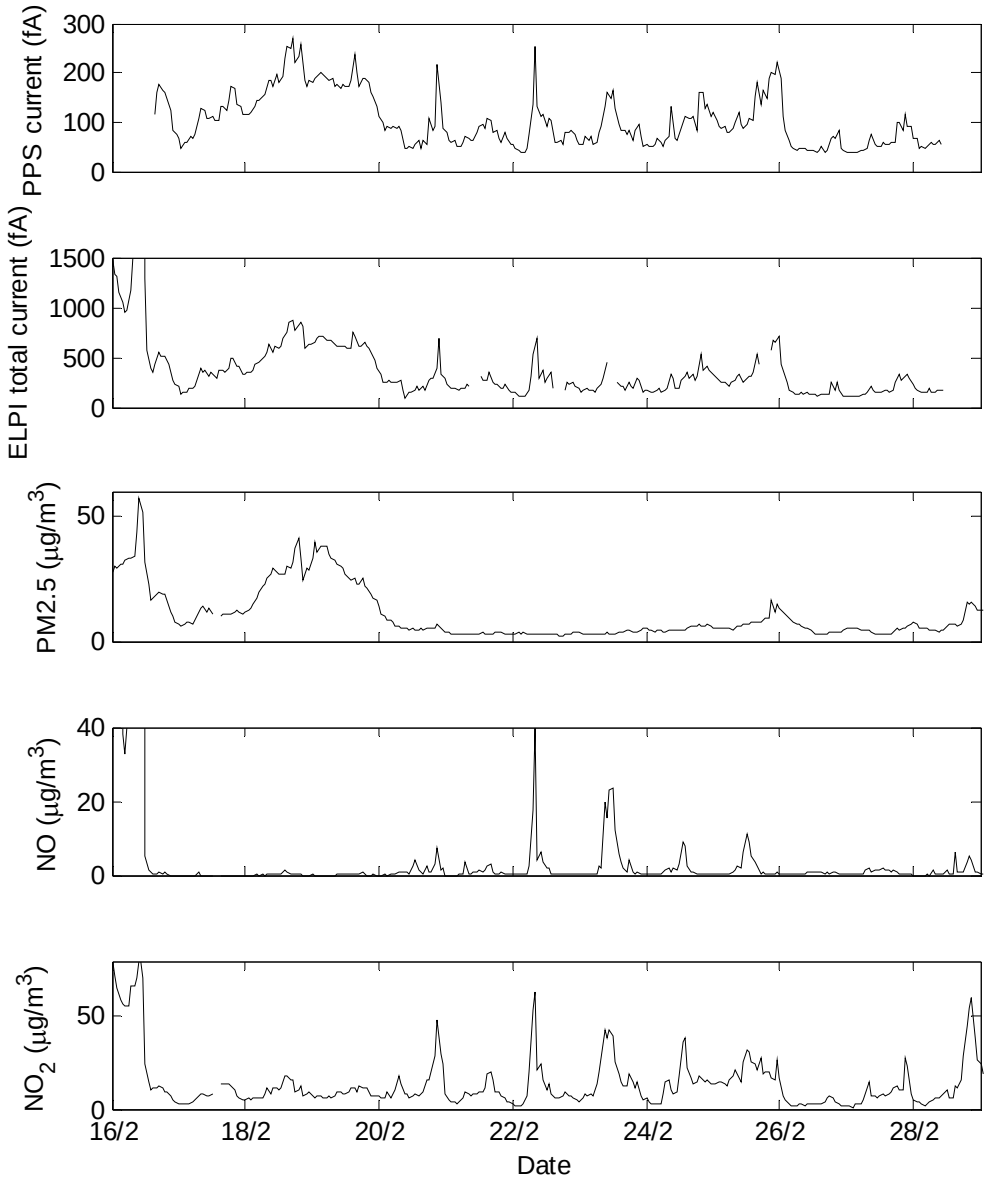

Figure 5 *Raw data of PPS-M and ELPI and PM2.5 and NOx concentration during the measurement campaign in Kattilalaakso (1 hour averages).*

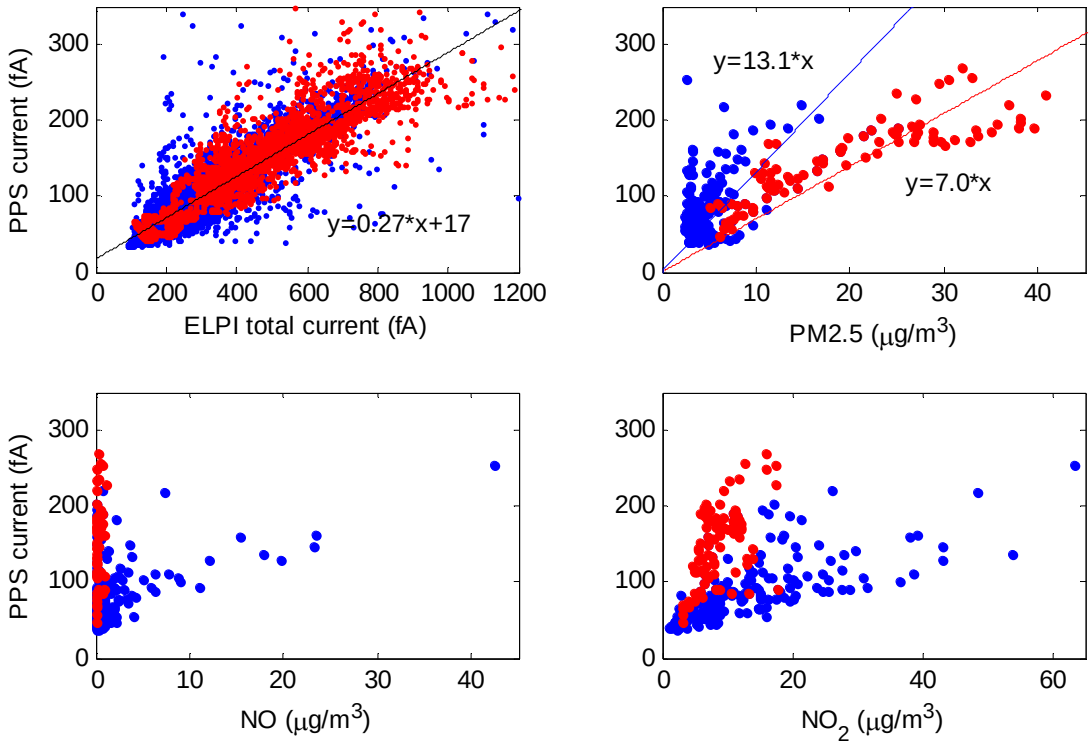

Figure 6 *The relation of the PPS-M raw signal (current) to the total current measured by the ELPI, PM2.5, NO and NO_2 levels. The measurement campaign was divided into two periods: high background ● and low background ●. ELPI versus PPS-M is presented as 1 minute average and other graphs as 1 h average.*

The particle size distribution was measured by the ELPI. The average distribution over the entire measurement campaign is shown in Figure 7. The average particle number distribution is bi-modal with one mode in the lower part of particle size range of the instrument, in particle size about 10 nm and the second mode between 100 and 200 nm. As the PPS utilizes physically similar charging method like the ELPI, electric currents measured by each individual ELPI stages are presented in Figure 7. The current distribution shows clearly, which particles dominate the raw signal of the PPS-M.

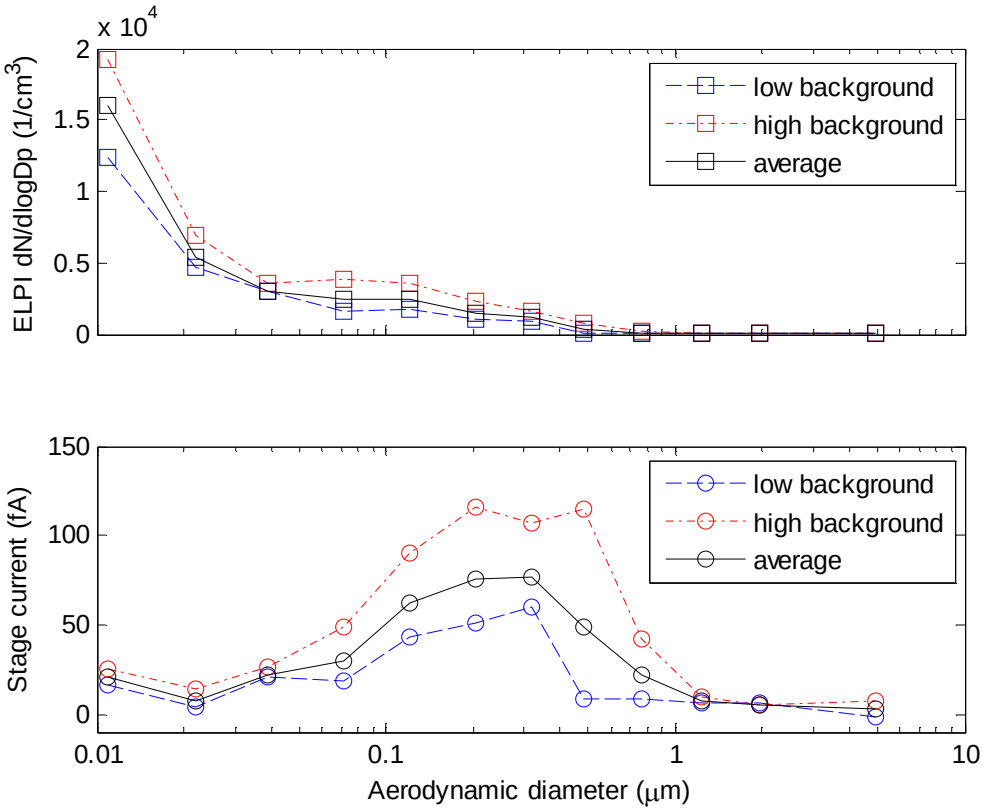

Figure 7 *The average particle size distributions over the measurement period in Kattilalaakso measured by the ELPI. Low and high background periods are shown separately along with the average. The number distribution (dN/dlogDp) is shown on top and the electric current distribution below.*

Stationary measurements in Malmi

The time series of the data from the measurements conducted in Malmi are presented in Figure 8. The PPS-M data is compared to particle number concentration measured by CPC, particle surface area concentration measured by NSAM, total electric current measured by the ELPI, PM2.5 and NO_2. Two days, 25th October (Thursday) and 27th October (Saturday), were selected for closer analysis. These are presented in Figures 9 and 10.

The basic characteristic of PM2.5 and NO_2 concentrations was the high variation of concentration levels between night time and day time. This was an expected result because the measurement station was situated close to Kehä I, one of the main roads in Helsinki area, and thus the concentrations in the measurement site were expected to follow the amount of traffic. The highest concentrations were detected during the morning hours, in the afternoon and in the evening. A small reduction in concentrations was detected just after the midday on many days. When a working day was compared to a weekend (Thursday and Saturday in Figures 8 and 9), some differences were

observed. During the weekend, the emissions were more uniformly distributed and the high concentration period in the morning was not detected at all.

According to the measurement data, the PPS-M signal correlates well with the total electric current of the ELPI and with the lung deposited surface area concentration measured by the NSAM. This is due to the operation principles of these instruments; all three aerosol instruments are based on the diffusional charging of aerosol particles. Figure 11 shows the PPS-M data as a function of total electric current measured by the ELPI, as a function of lung deposited surface are concentration measured by the NSAM, and as a function of PM2.5. Linear response with small deviation of data points is achieved when the PPS-M was compared to the ELPI and the NSAM. Instead, although the correlation plot shows that PPS-M signal is linearly proportional to PM2.5, the deviation of data is more significant. When a linear fit was made to the PPS-M and PM2.5 data, the slope was defined to be 30 fA/(μg/m^3). This is clearly higher than in Kattilalaakso. The difference in slope indicates again that the correlation between the raw signal of the PPS-M and PM2.5 depends on the particle characteristics. Compared to the measurements in Kattilalaakso, the mean particle size in Malmi was significantly smaller because of the vicinity of traffic.

It can be seen from Figures 8 and 9 that the high time resolution is an clear advantage when the traffic emission is studied. In our measurements the PPS-M, the ELPI and the NSAM were all providing data at rate of 1 Hz while NO_2 and PM2.5 are measured hourly basis. The high time resolution allows the detection of individual high concentration peaks. These peaks are clearly characteristic of traffic emissions. Using the instruments with high time resolution these variations in particles concentration can be observed and analyzed and further, in some cases or applications the concentration peak may even be traced to single vehicles.

The CPC time series shows most of the time the similar signal as the electrical instruments (PPS-M, ELPI, NSAM). However, there are some differences, for instance first hours of 25th October when the CPC detected much higher signal than electrical instruments compared to other hours of that day. This may be a result of different responses for different particle sizes. The electrical instruments (raw signals) are detecting signal ~D_p^n where n=1…1.5 whereas the CPC has practically no particle size dependency in the measurement range of the electrical sensors and it measures directly the particle number concentration. This difference can be seen in Figure 11 where the PPS-M signal is not as linearly proportional to the CPC concentrations as to the signals from the ELPI or the NSAM. It should be noted that the CPC was counting occasionally the concentrations higher than 300 000 #/cm^3 which is the maximum concentration reported by manufacturer (TSI Inc. 2013). The instrument measures higher concentrations but the signal reliability is probably limited during these periods.

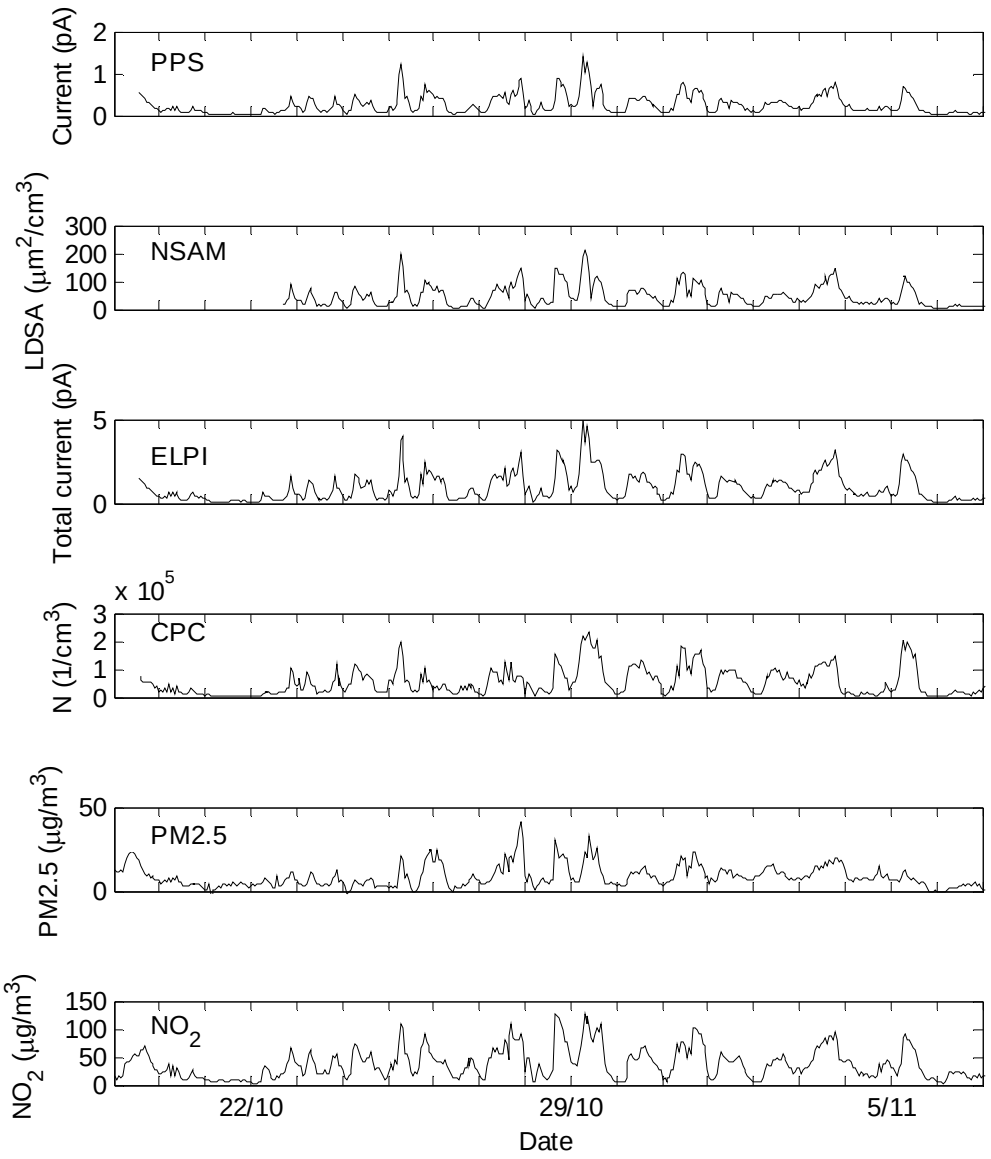

Figure 8 *The time series of Malmi measurements. Each measurement point represents one hour average signal.*

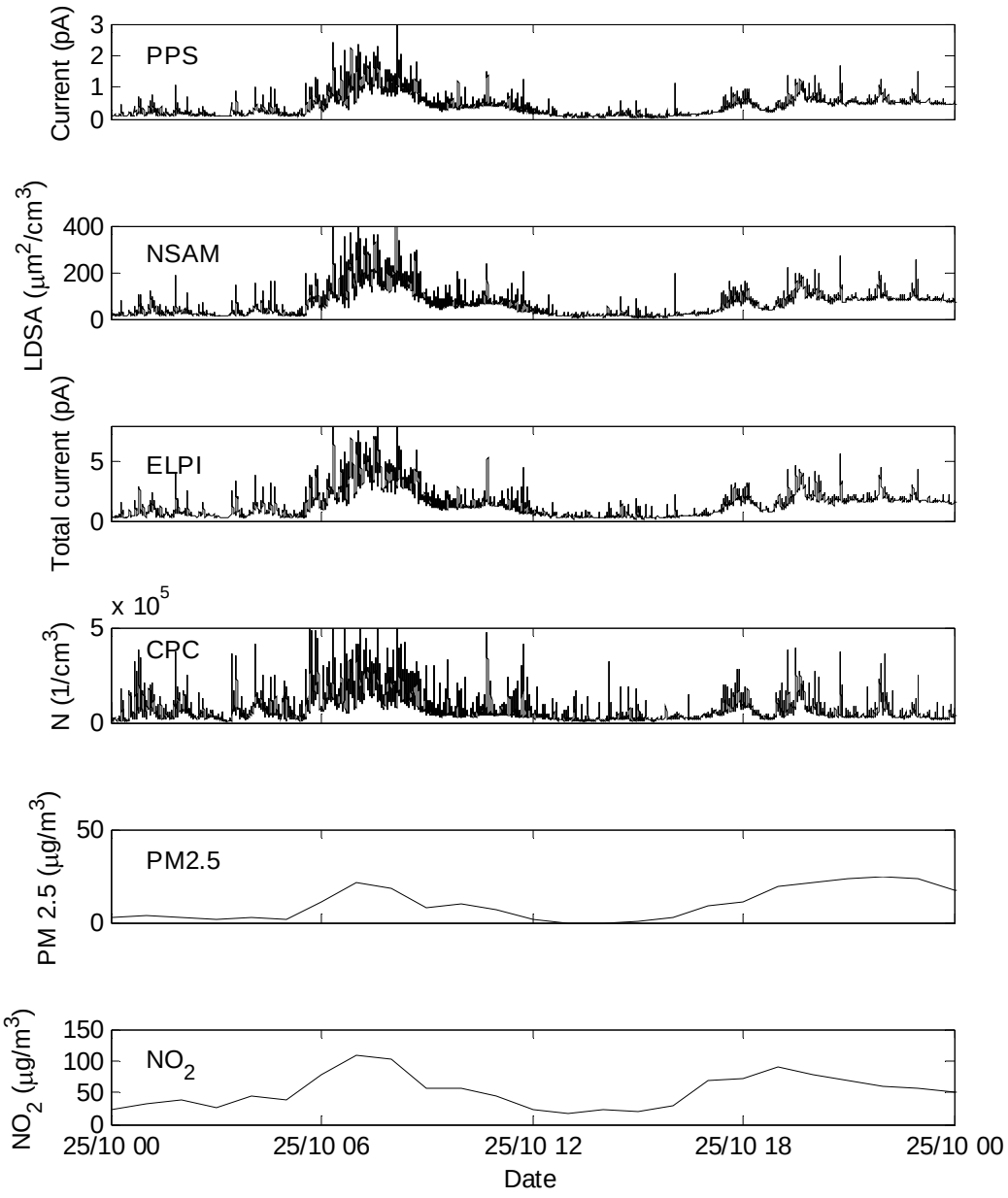

Figure 9 *Malmi 25th of October (Thursday) in closer detail. In this series PPS-M, NSAM, ELPI and CPC are all measuring at rate of 1 Hz. The high sampling rate reveals the rapidly changing particle concentrations in traffic related emissions.*

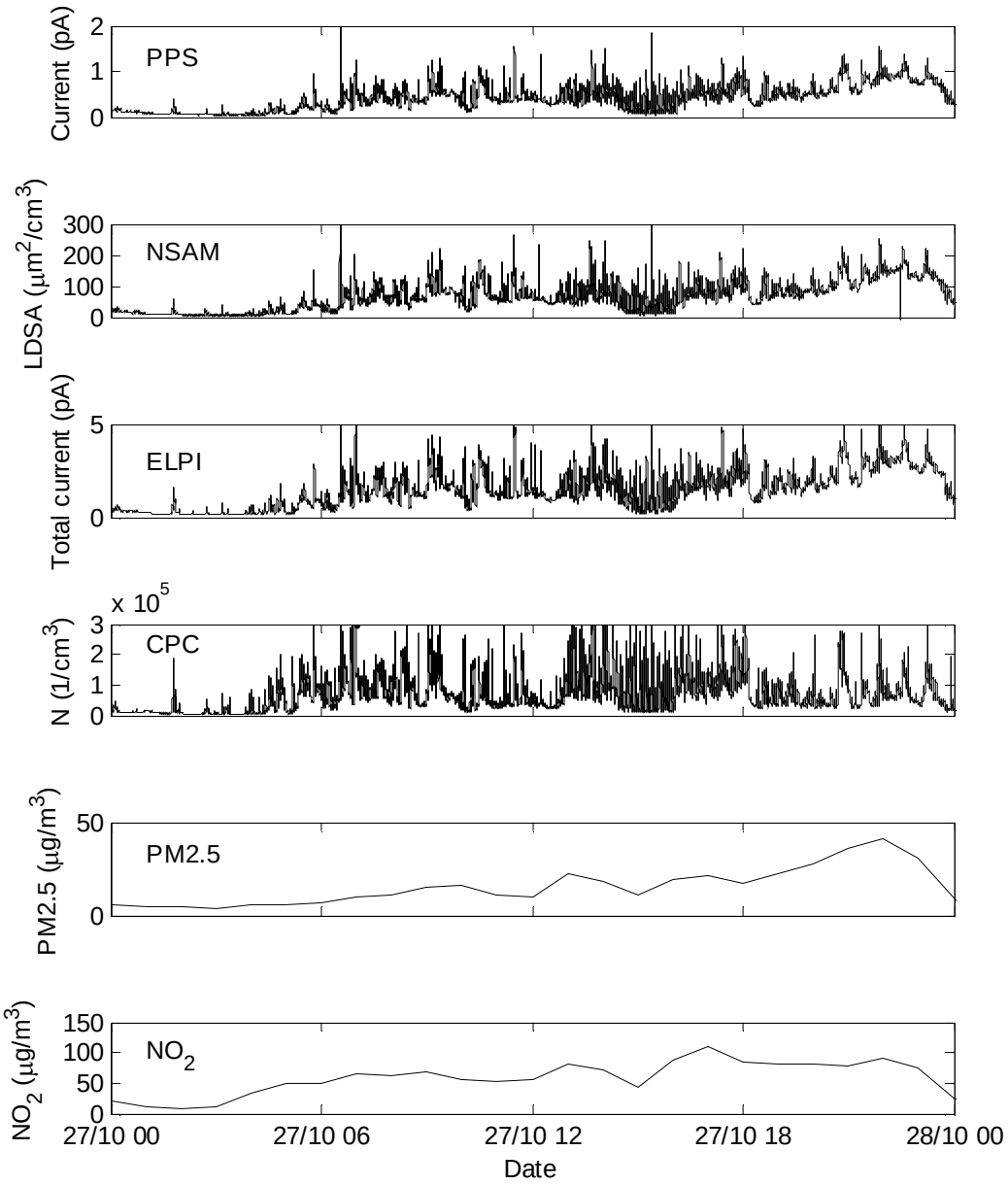

Figure 10 *Malmi 27th of October (Saturday) in closer detail. In this series PPS-M, NSAM, ELPI and CPC are all measuring at rate of 1 Hz.*

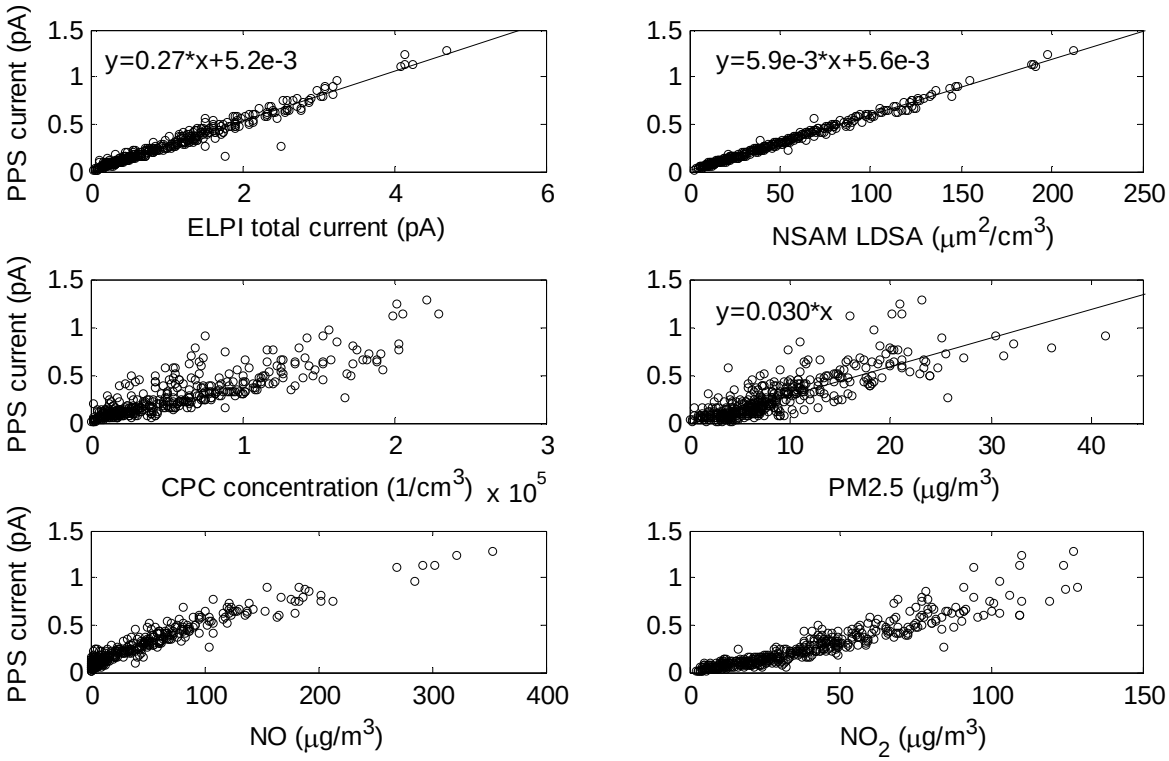

Figure 11 *The PPS-M signal (electric current) as a function of the ELPI total electric current, NSAM lung deposited particle surface area concentration (alveolar deposition) and PM2.5. The PPS-M signal is also shown as a function of NO and NO_2 concentrations because they are known emission compounds. The data is from measurements conducted in Malmi site. Each point is a one hour average.*

The size distribution was measured by the ELPI. Average number distribution over the entire measurement is presented in Figure 12. The average distribution was bi-modal with one mode in particle sizes ~10 nm range and the other between 30 and 100 nm. The second mode was in significantly smaller particle sizes than in Kattilalaakso. This difference can be explained by the differences in particle sources and the differences in the distances between the particle source and the measurement site. The Malmi site was situated close to a high traffic road and thus the measured aerosol mainly consisted of fresh exhaust aerosol. In general, the particle size distributions and concentrations measured in the measurement station of Malmi were typical for traffic and in line with previous studies conducted in similar environments.

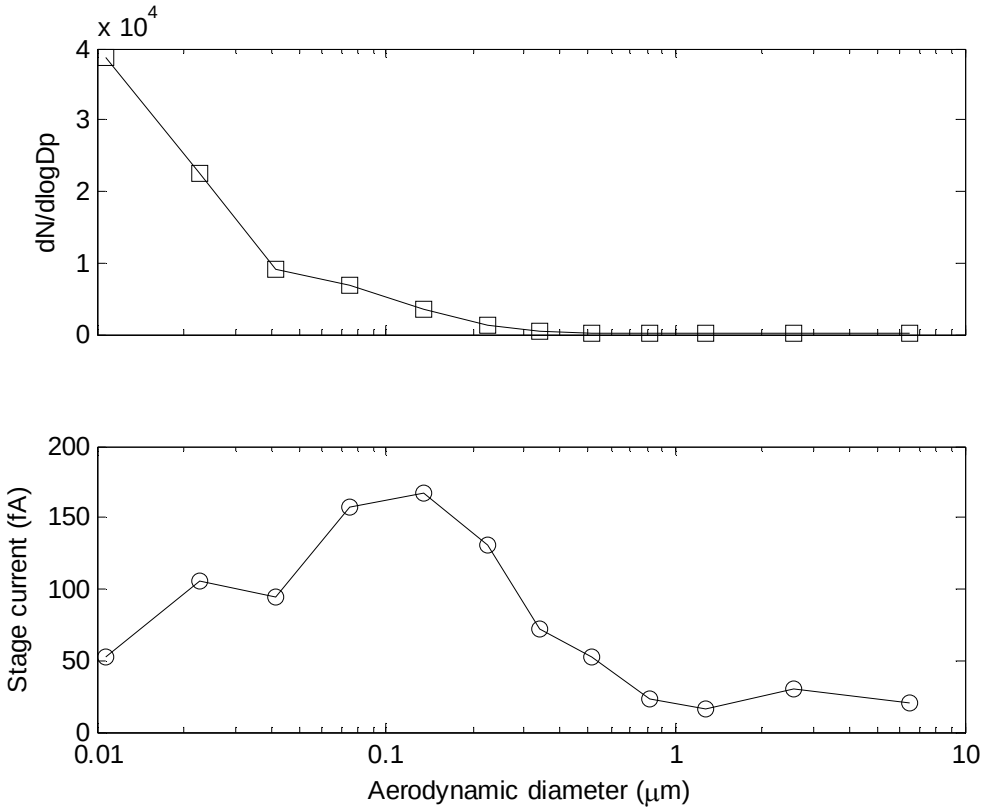

Figure 12 *The mean particle distributions measured by ELPI in Malmi. The number distribution (dN/dlogDp) is shown on top and the electric current distribution below.*

Measurements by mobile laboratory

The time series of the PPS-M data and the NSAM data from the measurement conducted by mobile laboratory are presented in Figure 13. Both the instruments, PPS-M and NSAM, detected nearly constant background aerosol concentration. In the PPS-M data this part of aerosol caused nearly constant electric current level from 0.15 to 0.3 pA and in the NSAM lung deposited surface are concentration from 40 to 100 $\mu m^2/cm^3$. We think that this part of aerosol forms the urban background while the aerosol related directly to traffic is visible as sharp peaks, in the PPS-M data with electric currents up to level of 12 pA.

The electric current measured by the PPS-M correlates well with the lung deposited surface area measured by the NSAM. Both the instruments produced almost identical time series as shown in Figure 13. The measurement data is also shown in scatter form in Figure 14 where the electric current measured by the PPS-M is presented as a function of lung deposited particle surface area concentration. In order to reduce the effects of different time responses originating from the instruments as well as from the measurement setup, the signals were calculated as 10 s averages. Results show that the signal of the PPS-M correspond to the NSAM data. The scatter compared to other measurements is higher because of a shorter averaging time.

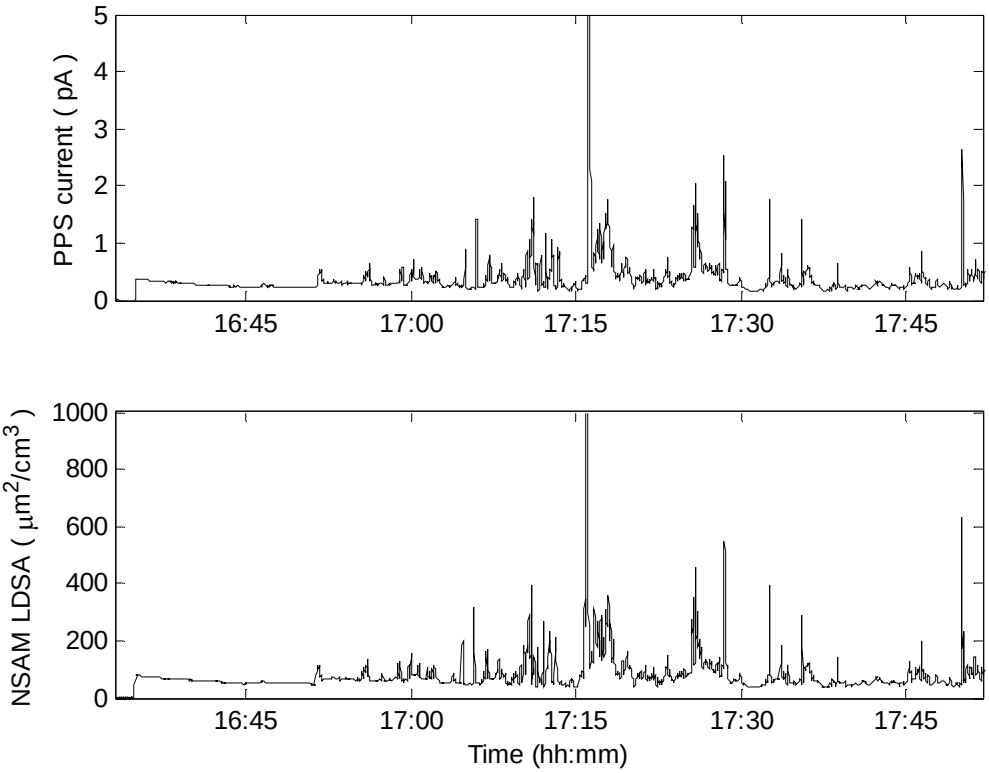

Figure 13 *PPS-M data compared to NSAM measuring lung deposited particle surface area concentration in alveolar deposition mode. Both devices are sampling at a rate of 1 Hz. This measurement was conducted in a moving vehicle.*

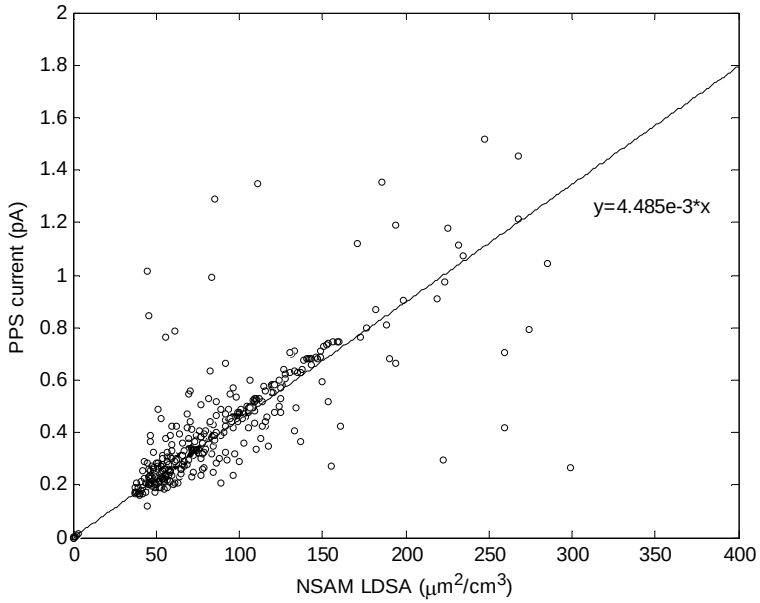

Figure 14 *The electric current measured by PPS-M as a function of alveolar deposited particle surface area concentration measured by NSAM. Each point is a 10 s average.*

In the mobile laboratory measurements, the particle size distribution was measured by the ELPI as in stationary measurements. The mean distributions for particle number concentration and electric current are presented in Figure 15. The mean particle number size distribution was similar to the distribution measured at the Malmi site with one particle mode in ~10 nm and the second between 30 and 100 nm. In both measurements, the main particle sources were presumably vehicle engine emissions, and the measurements were conducted close to the emission sources.

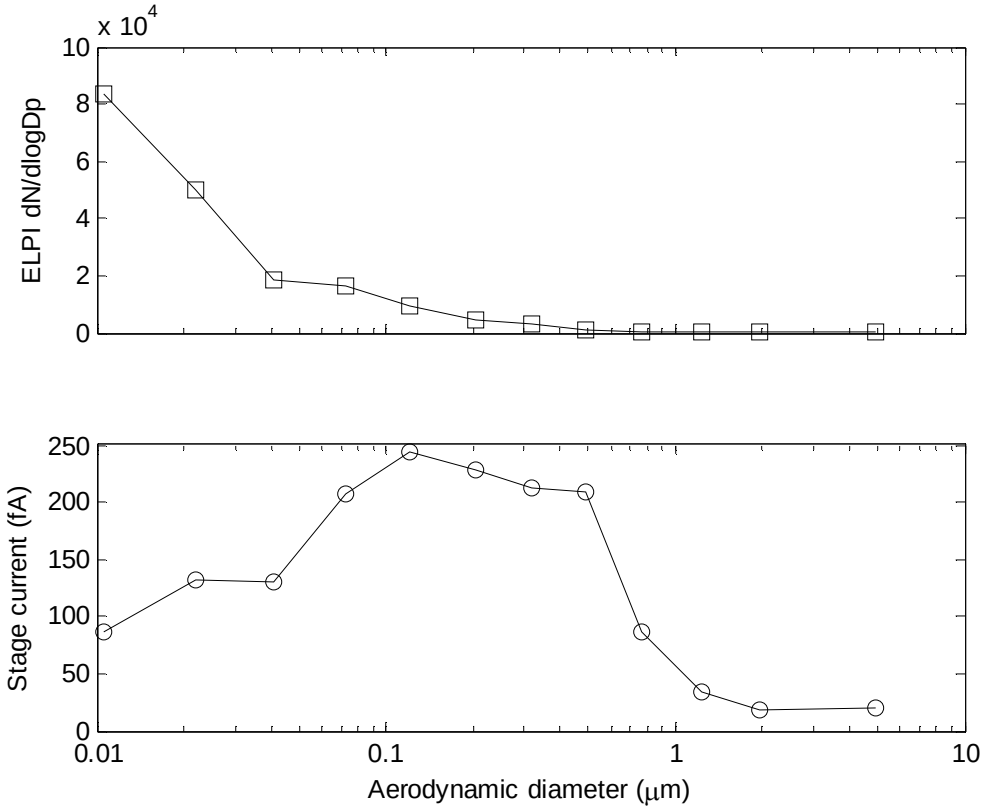

Figure 15 *The average of particle size distribution measured by ELPI. Mobile laboratory measurement in traffic.*

The PPS-M design allows the measurement of rapid changes in particle concentration. This ability is presented in Figure 16. The PPS-M allows sampling up to 100 Hz rate but a traffic related concentration peak was here measured at 1 Hz sampling rate to reduce amount of data and to match the rate with the reference instruments. The peak was recorded at location N60°10.8531 E024°57.6078 on Sörnäisten rantatie which is a one of the main streets in Helsinki. The high concentration was caused by small particles which can be seen in the size distribution presented in Figure 17. The particle number size distribution was dominated by one particle mode below 10 nm in particle diameter and most of the electric current was measured by the 2nd stage of the ELPI with geometric mean diameter of 22 nm.

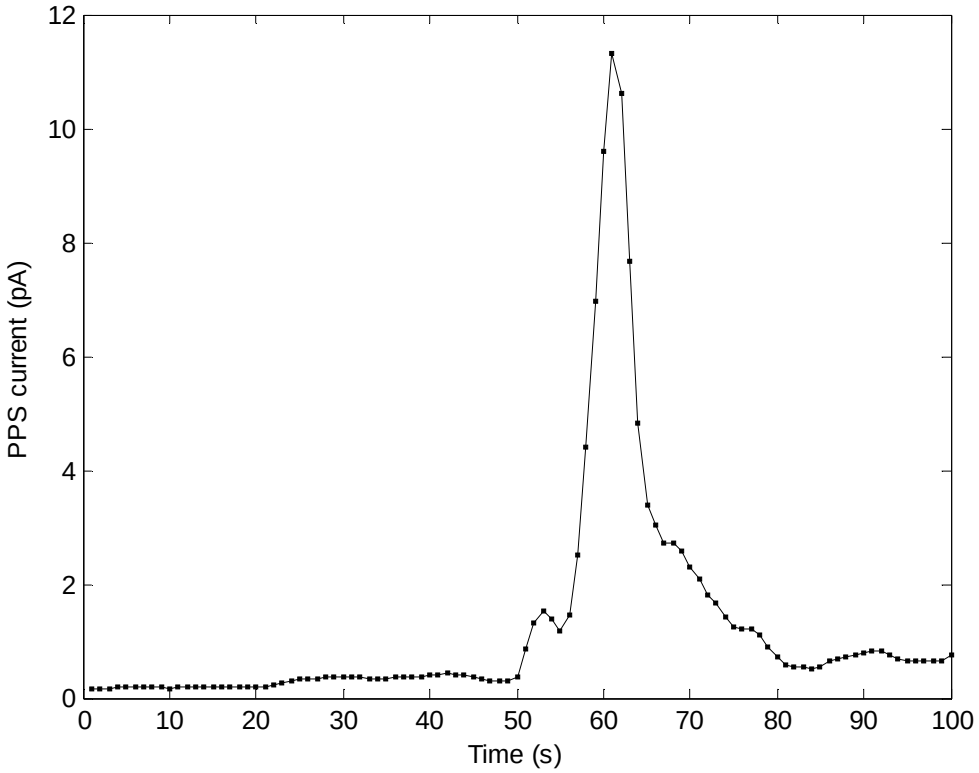

Figure 16 *PPS-M measuring at 1 Hz. The data illustrate the fast response for rapidly changing particle concentrations. The peak appeared at time 17:16 in the Figure 13.*

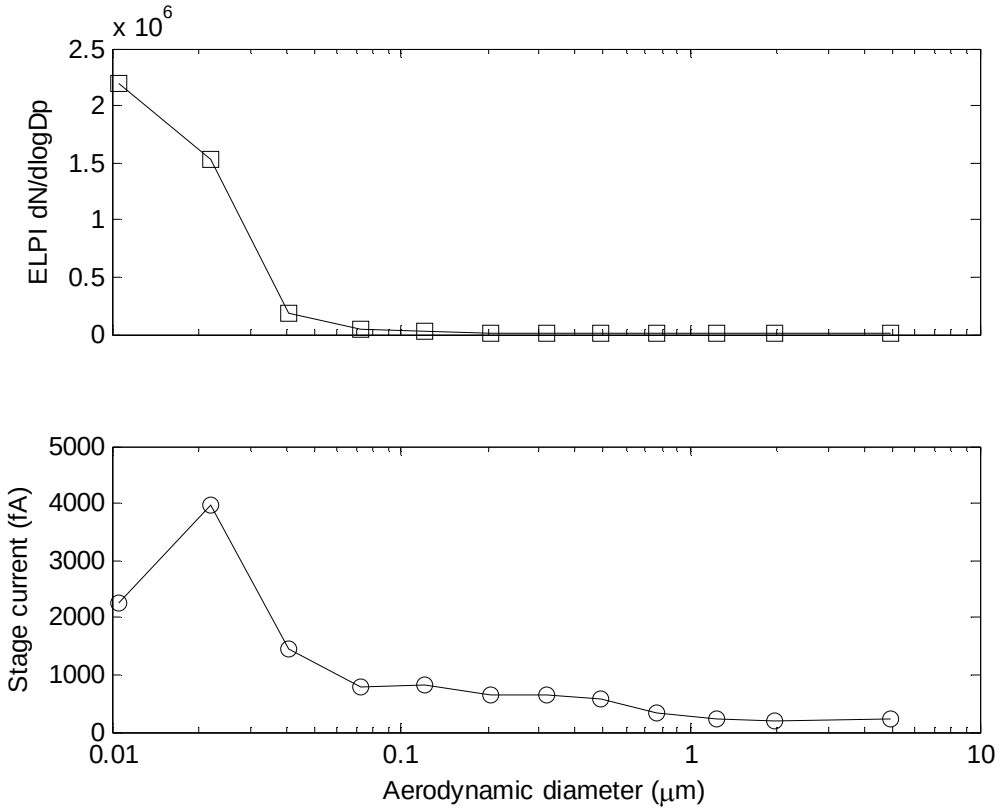

Figure 17 *The particle number size distribution and the electric current size distribution measured by ELPI during the high concentration peak recorded at 17:16.*

CONCLUSIONS

In this study, the PPS-M sensor was used to measure outdoor air particle concentrations in urban environments. The measurements were conducted in two stationary sites: in small-house residential area (winter 2012) and close to a road with high traffic (autumn 2012). The third measurement was conducted using a sensor installed into the mobile laboratory (winter 2012). The PPS-M was not equipped with any pre-conditioning of the sample. Due to the large measurement campaigns, the reference instrumentation was large. In this report, we have used only some of those instruments, because the focus has been in general function of PPS-M.

Most important observations of our studies are:

- The PPS-M sensor can be used for long-term outdoor aerosol measurements even without pre-conditioning. Major problems were not detected.

-The correlation between the raw data of the PPS-M and PM2.5 was depended on the measurement. According to linear fits to the measurement data, the slope was 7.0 fA/(μg/cm^3) in Kattilalaakso during a high long-range transported background aerosol period and 13 fA/(μg/cm^3) during a low

background period. In Malmi, where the aerosol mainly consisted of the fresh exhaust particles, the slope was 30 fA/(μg/cm^3).

- The signal (electric current) of the PPS-M was linearly proportional to the lung deposited particle surface area concentration measured by the NSAM and to the total electric current measured by the ELPI. The correlations between the signal of the PPS-M and other instruments based on the diffusion charging of particles were always practically the same despite of the variation of the studied aerosol.

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