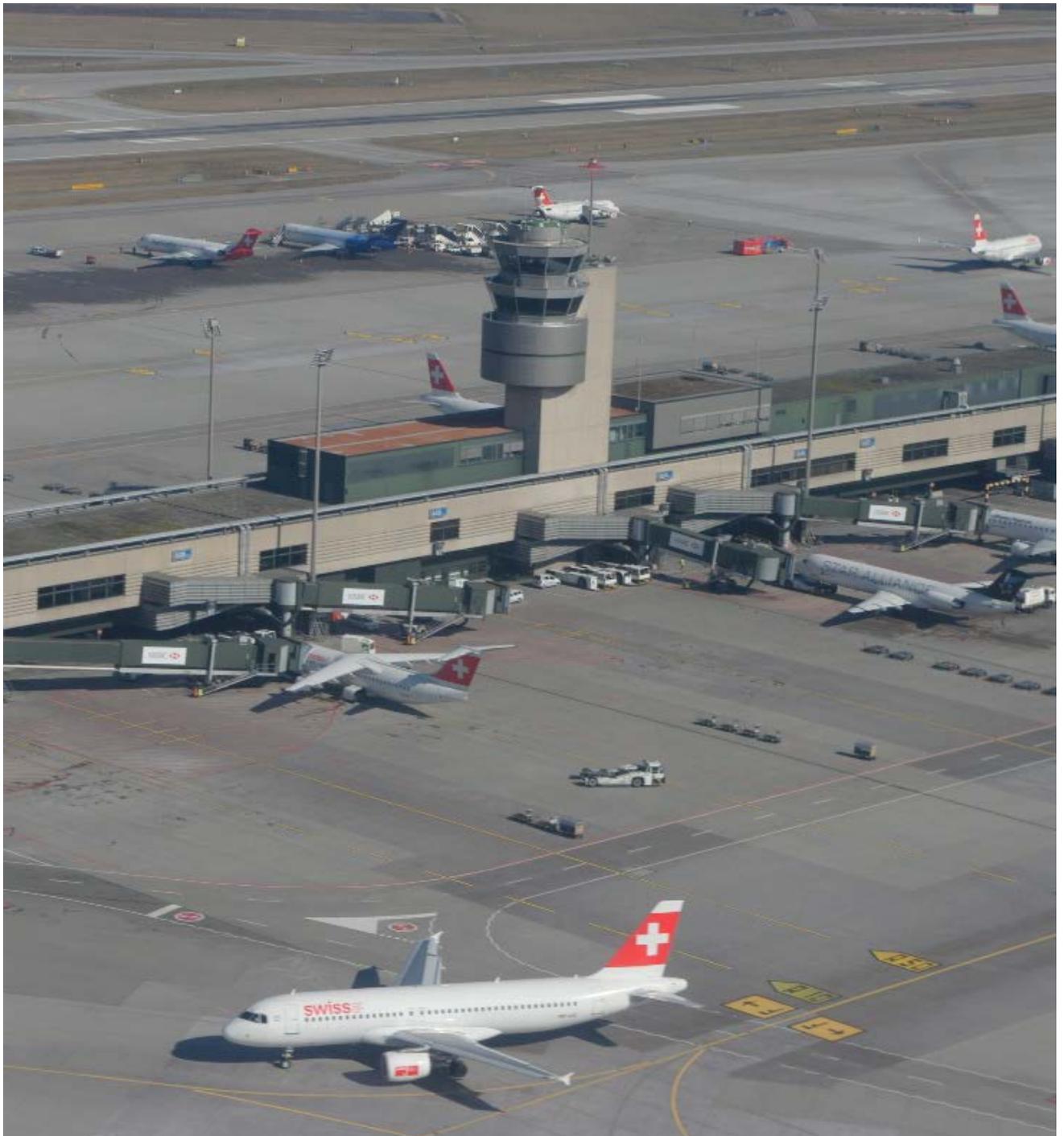


# Ultrafine Particle Measurements At Zurich Airport



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## 1. Introduction

Zurich Airport is located a few kilometers North of the city of Zurich. With 265,000 aircraft movements and 26.3 million passengers in 2015, it is part of a busy and densely populated region. It's Switzerland's largest airport and a European mid-size hub. Local air pollutants like NO<sub>2</sub> have been monitored at several sites at the airport and its vicinity and extensively modelled. To this end, those mechanisms (emissions – dispersion – concentrations) are well understood and have been documented for years [FZAG, 2013]. However, there is only little knowledge and data for ultrafine particles (UFP, particles with a mean diameter of <0.1µm), and public interest in this topic is increasing. Only single measurements have been conducted on the airport apron in 2012, covering four locations for one to two hours each.

In consequence, Zurich Airport has set up a measurement campaign aiming at better understanding the spatial and temporal distribution of ultrafine particles at the airport itself and one reference station outside. Within a time period of five weeks, a network of 10 stations has been operated simultaneously, collecting data of particle number, diameter and lung-deposited surface area (LDSA, which is a metric that can be used to describe biological effects) together with information on meteorological parameters (wind, temperature, precipitation) and aircraft traffic information (movements, fuel burn, CO<sub>2</sub>).

The main questions to be answered in this exploratory study were:

- What are the particle number, diameter and LDSA and their variability at the various stations during the campaign duration?
- What are the average particle numbers and diameters among selected stations under specific circumstances of meteorology or operations?

Particle number counting instruments measuring ambient air particle concentrations usually count all UFP particles, irrespective of their origin and chemical composition. This study cannot and must not be used to relate UFP concentration results to health effects. As particle number counters report total number of particles without any information on chemical composition and without knowledge of health impact of different species, the measured levels of UFP number concentrations are not more than an inventory of the UFP concentrations observed at and near the airport.

UFP are very different in shape, from liquid droplets to solid complex, non-symmetrical structures. The sizing instruments report the so called “mobility diameter”, which does not take characteristics into account.

## 2. Measurement Setup

Modern jet aircraft engines are known to produce high numbers of very small particles, with mean mobility diameters of the non-volatile (=solid, mostly soot) particles in the size range of 20-45nm (nanoparticles), depending on engine operating conditions (Lobo et al 2015). Volatile particles may also be present with even smaller diameters, vehicle exhaust emissions also produce volatile particles in the same size range

The UFP fraction of solid particles in the jet engine exhaust however are clearly smaller than those found in other common combustion processes, such as vehicle exhaust or domestic wood burning (Handbuch Verbrennungsmotor, 2017). For such small particles, diffusion losses in sampling lines are much higher, and they are harder to detect in many standard aerosol instruments due to their small size. Thus, nanoparticle measurements for jet engine exhaust are more challenging than those of e.g. vehicle exhaust. At the same time, the large difference in particle size compared to vehicle exhaust may allow for a distinction of the two sources via particle diameter, more precisely, if only the UFP fraction of solid particles is measured

The miniature diffusion size classifier (miniDISC, Fierz et al. 2011) was selected as a nanoparticle detector in this study because it has some advantages that make it ideal for this type of study: it is relatively compact, needs little power and can operate under a wide range of temperatures; all of which allowed simple installations at the airport. Compared to the standard device for particle number monitoring, the Condensation Parti-

cle Counter (CPC), it needs no working fluid and can thus run unattended for longer periods of time; and furthermore, it also measures an average particle diameter which may be useful for source apportionment as discussed above. While the particle concentration range of the device is well suited to this measurement campaign ( $10^3 - 10^6$  particles per  $\text{cm}^3$ ) the upper limit was sometimes reached), the jet engine particles are quite close to the lower end of the specified diameter range of 10-300nm. Special care was taken in this study to ensure that the devices were operating properly at this outer edge of their specifications, namely:

- (1) The devices were all freshly calibrated just before the start of the campaign.
- (2) The devices were inter-compared in the lab using particles in the expected size range before the start of the campaign and the differences between the devices at 20nm particle diameter were noted.
- (3) The devices were inter-compared for a second time after the end of the campaign.
- (4) During part of the campaign (May 2016), a scanning mobility particle sizer (SMPS) was operated in the main measurement station on Pier A, thus allowing a direct comparison of the miniDiSC data with that of a more traditional device. The results show an excellent correlation with deviations of 10%-20%.

The inter-comparison of the freshly calibrated devices showed a very good agreement among the 10 devices tested, with maximal deviations of 6% in particle diameter, 11% in particle number and 14% in LDSA. After the campaign, the differences were clearly larger with maximal deviations of 20% in particle diameter, 20% in particle number and even 40% in LDSA. It should be noted that this is the maximal variability of the devices, i.e. the difference between the device displaying the highest and the one displaying the lowest concentration; the average variability was clearly lower. We can thus conclude that all devices were operating properly during the campaign, and that inter-instrument variability or effects of drift in the calibration were typically of the order of 10%.

The measurement locations were grouped into three clusters and the stations placed accordingly: Transect North-South of the main long-haul departure Runway 16 to capture UFP near aircraft operations (stations 1, 2, 3, 4), transect West – East and a background station in line with predominant wind direction (stations 1, 5, 6/6X, 7, 9, 10) and a transect apron North-South (stations 1, 5, 6/6X, 7; see figure 1) to assess aircraft and handling emissions likewise. Station 1 has the same location as the permanent air quality monitoring station that covers  $\text{NO}_x$ ,  $\text{NO}_2$ , Ozone and  $\text{PM}_{10}$ . In total, ten locations were selected for measurements.

No.	Location	Characterization
1	Roof Pier A	Aircraft handling, aircraft taxiing; 350-400m distance to Runways 28 (short haul take-off and landing) and 16 (long-haul take-off)
2	Meteo Garden	Aircraft traffic: Landings Runways 14 (180m distance) and 16, take-off long-haul Runway 16 (450m distance)
3	Stands Papa	Aircraft taxiing to Runway 16; departing aircraft (400m distance)
4	End of RWY16	Departing long-haul aircraft Runway 16 (400m distance; aircraft altitude 200m )
5	Apron V5	Airside traffic, aircraft handling, landing and take-off Runway 28 (270m distance)
6/6X	Apron courtyard	Airside traffic, aircraft handling, pushback, aircraft idling and taxiing
7	Stands Charlie	Airside traffic, aircraft handling, aircraft taxiing
8	Helipad West	Airport fence, upwind. Between cantonal road (370m) and Runway 16 (460m distance)
9	Entrance Gate 109	Airport fence, downwind. Between motorway A51 (250m distance) and Runway 28 (450m distance)
10	Cemetery Kloten	Background, little traffic, (1,900m from airport fence); long-haul overflights (1,500m/ground)

Table 1 Measurement locations and their characteristics

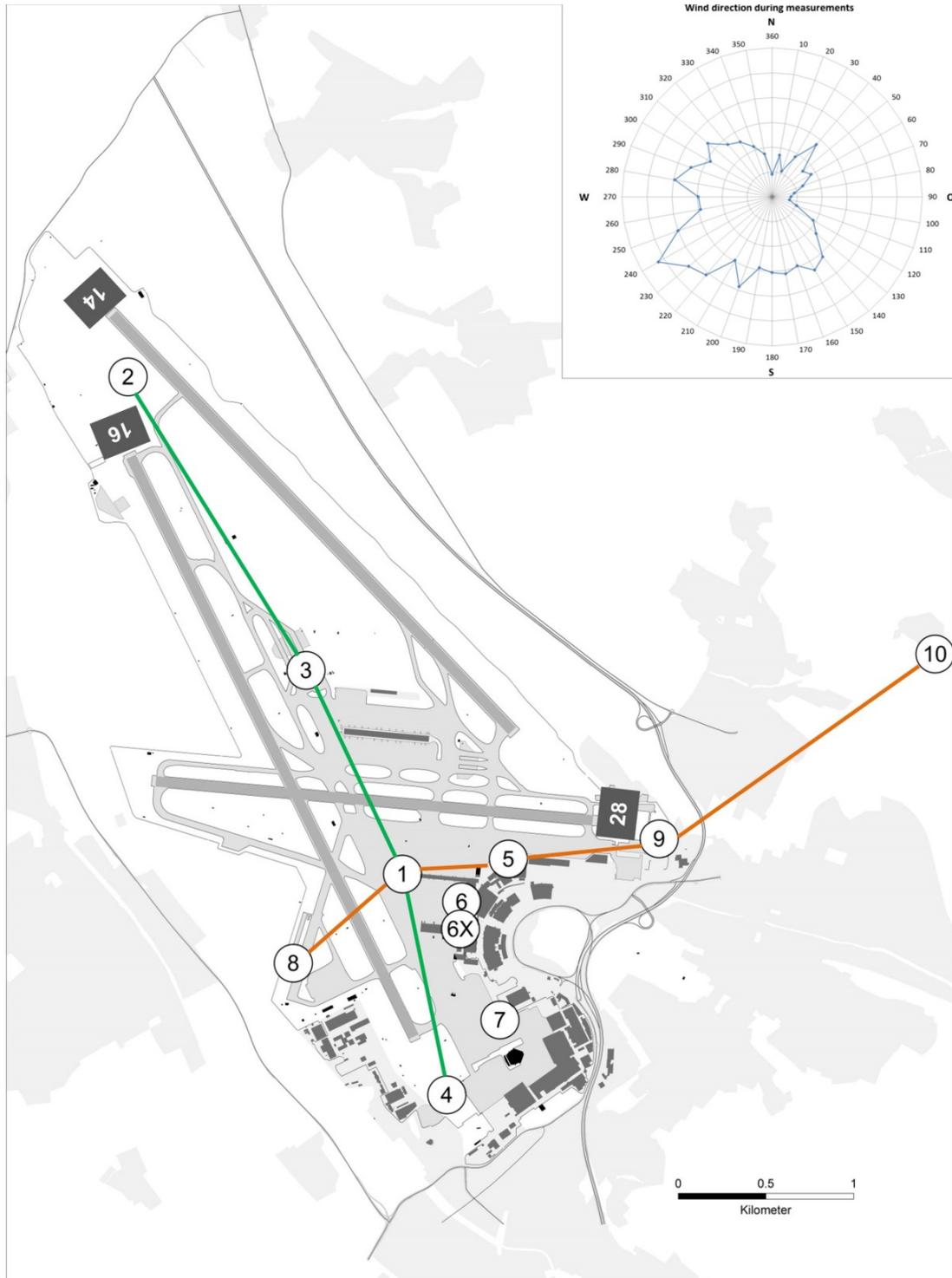


Figure 1 Zurich Airport layout with UFP monitoring stations and predominant wind field

All stations were equipped with a Miniature Diffusion Size Classifier (MiniDiSC) with a data capture frequency of 1s [Fierz, et al. 2011]. All aerosols are being accounted for (volatile and non-volatile) within a size range of 10-300nm. These devices are rather compact and were run on external power, thus being well suited for the campaign at an airport, requiring low maintenance. The systems were all calibrated in parallel, ensuring like-

for-like measurements among the devices. The campaign ran from April until June, 2016 (5 weeks) to capture various weather conditions and compensate for some potential monitoring gaps.

The main measurement station (1) was additionally equipped with a Scanning Mobility Particle Sizer (SMPS TSI 3080 with CPC TSI 3775) with a scan every minute for part of the campaign to gain additional information for particle size class distribution. The station was operated during part of the campaign.

All station maintenance and data download were performed weekly and the raw data checked for quality and consistency.

### 3. Results

#### 3.1. Number concentrations and particle size

The diurnal particle number concentrations and average mobility diameter for monitoring stations along the East-West transect are presented in figure 2. The stations represent predominately upwind (no 8), downwind (no 9), hot spot (no 1) and background locations (no 10). For comparison, the aircraft activity is shown as LTO (landing and take-off) CO<sub>2</sub>-emissions (grey area). LDSA values range from 18nm<sup>2</sup>/cm<sup>3</sup> at night to 135nm<sup>2</sup>/cm<sup>3</sup> during peak time at 0700. The diurnal LDSA pattern also corresponds well with the particle number concentrations.

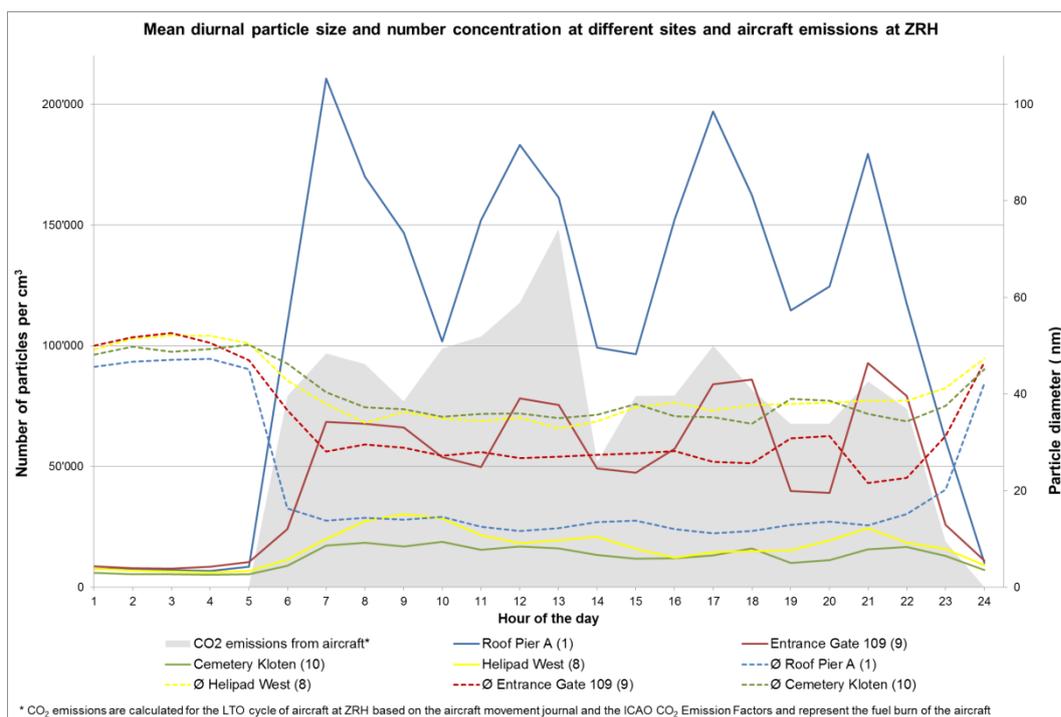


Figure 2 Diurnal particle number and size distribution at selected monitoring sites, hourly average (solid lines: particle numbers concentrations; dotted lines: average mobility diameters; grey area: kg CO<sub>2</sub>, not scaled)

Station 1 (Pier A) shows the highest number concentrations at the lowest particle size and at the same time the most distinct diurnal variation in both particle numbers and particle size. This could be expected from the location in the center of the airport and aircraft activity. Station 9 (Entrance Gate 109) which is located 1,450m downwind at the airport fence compared to station 1 shows half the numbers and twice the size of particles

while the station 10 (Cemetery Kloten), 3,300m downwind the airport station 1 shows low particle numbers with high diameters. Station 8 (Helipad West), 1,030m upwind the airport station 1 also shows low numbers with high diameters despite being only 460m distant from the main long haul aircraft take-off runway. However, this station is 370m downwind the cantonal road West of the airport and will thus also be influenced by those emissions.

### 3.2. Variability of number and size of particle

The variability of the particle number concentrations was very high in two ways. First, the variability between the stations over the same time period at the airport itself spans from the station 8 (Helipad) with 16,000pt/cm<sup>3</sup> (hourly average) to the station 6X (Emergency stairs) with 139,000 (factor of 8.6). The second variability is observed within the station results themselves. Station 5 (V5 Apron) rendered values from 1,400 (minimum) to 786,000pt/cm<sup>3</sup>, with a mean of 104,000pt/cm<sup>3</sup> (again hourly averages over the whole campaign duration). Even the background station 10 (Cemetery) showed a span from 1,300 to 100,000pt/cm<sup>3</sup> with a mean value of 12,000pt/cm<sup>3</sup>. The lowest values occurred during night time and the highest values during day time peak hour traffic, as also can be seen in figure 2.

The average diameter variability is less pronounced. It is a factor of 1.9 between the lowest (station 1, Pier A, 21.7nm) and the largest (station 2, Meteo Garden, 40.5nm). Within the same station, the variability factor was highest at station 9 (Gate 109) with a low of 7.9nm and a high of 103nm where the average was 33.5nm.

### 3.3. Aircraft activity influence on number and size of particles

In order to assess the influence of aircraft activities on number concentrations and size, data from the parallel operated SMPS has been evaluated for three timeslots: 0700-0800 local time with maximum particle emissions from aircraft activity, 1400-1500 with minimum aircraft activity during the day and 0200-0300 with no aircraft activity during the night curfew (see figure 2). The classifier was set to a range from 6.4nm to 217nm. The results in figure 3 confirm results from other studies [ACI, 2012] that aircraft emissions tend to produce larger numbers of particles at lower sizes, with peak emission particle diameter at 16nm, low activity diameter about the same and only no activity diameter being at 35nm (figure 3, log scale). In addition, aircraft particle number emissions tend to dominate over those of ground support equipment or other vehicles.

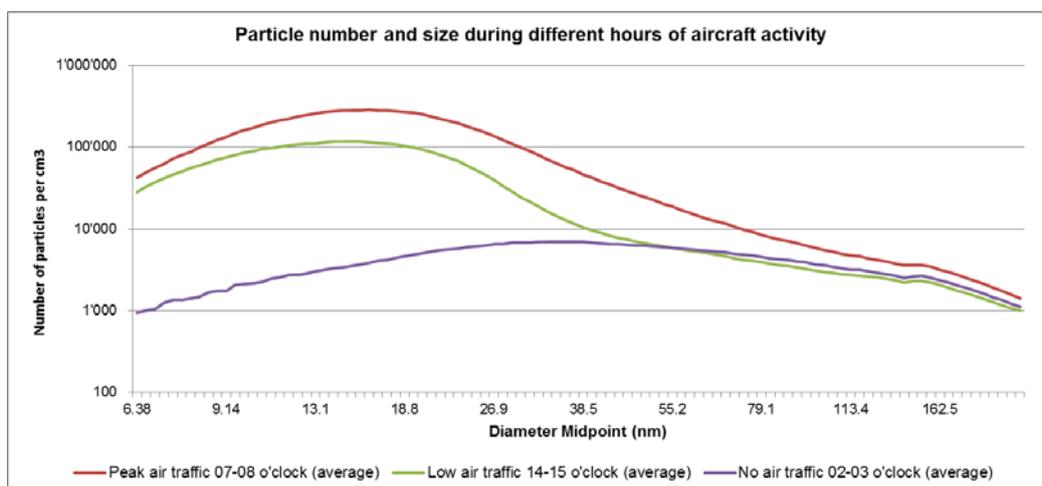


Figure 3 Aircraft activity dependent particle number and size distribution (log scale)

### 3.4. Meteorological influence

Wind speed and direction were analyzed to identify their influence on particle number and size variability. The wind analysis was first done at the same station (2, Meteo Garden) during always the same one hour of activity – between 10:34 and 11:34 – but different wind situations (figure 4). Clearly, number concentrations and size and thus the “pattern” vary considerably depending on the wind direction where the measurement location may be upwind, downwind or crosswind to the airport center. The Northeasterly wind likely shows the influence from landing traffic on Runway 14, while the Northwesterly wind brings background concentrations and Southeasterly wind (factor 10 higher illustrated) shows the impact of departing aircraft on Runway 16 and the influx from the center of the airport and all activities there.

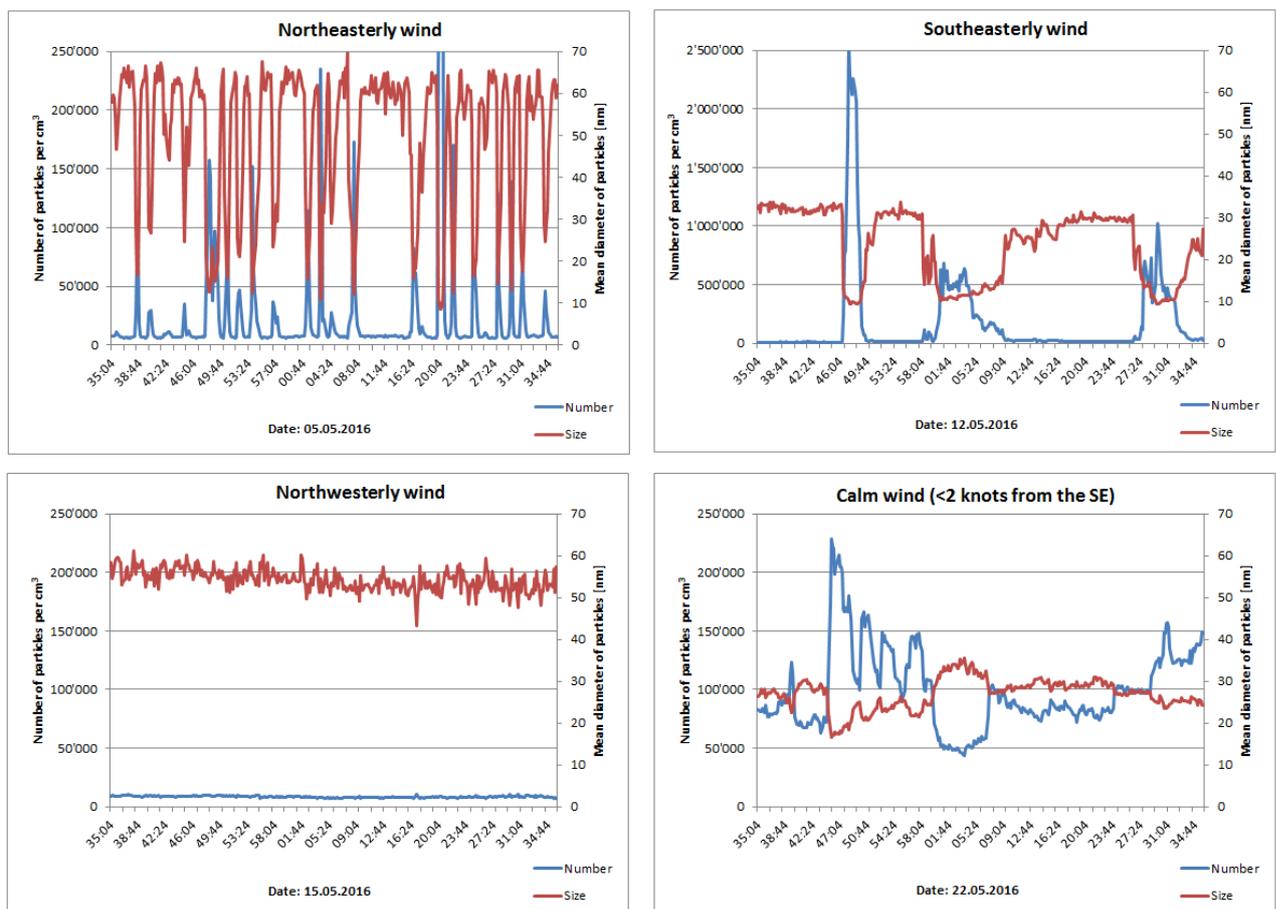


Figure 4 Variability of particle number and size due to different meteorological conditions, but same activity profile (Meteo Garden, no 2)

The second comparison was done along two transects, one being North-South (Runway 16, along the stations 2-3-1-4) and one being West-East (along the stations 8-1-5-9-10) (Fig. 5). The North-South transect shows similar results for Northerly (330°-30°) and Southerly (150°-220°) winds. The high peaks from Roof Pier A drop by at least two thirds to either airport boundary station (2 and 4). The West-East transect primarily shows the impact of the high activity profile around Pier A und the apron (stations 1 and 5). With Southwesterly winds

(220°-280°), peak values are reached at Apron V5 station (5), with Northeasterly winds (30°-90°) at Roof Pier A (1). For both wind directions, peak numbers drop also by two thirds within approximately one kilometer distance and even by 80% within 3km distance.

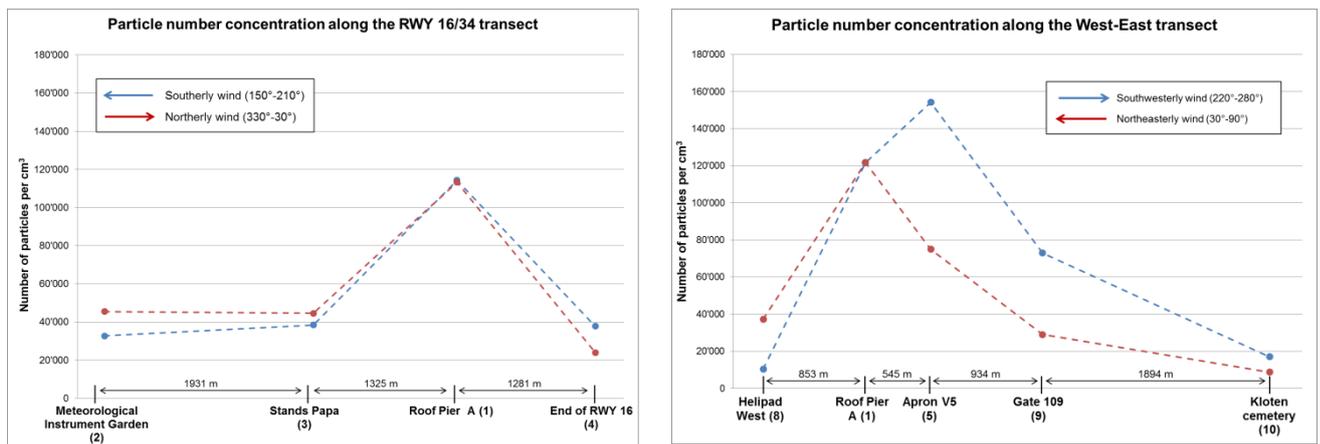


Figure 5 Particle number concentrations along the North-South and West-East transects

The question about the influence of particles emitted at various aircraft elevations on the ground concentrations could not be fully answered. The limited data, however, indicates a decrease of particle numbers from 30,000prt/cm<sup>3</sup> at measurement station 4 (end of Runway 16, approximately 180m above ground) to 17,000pt/cm<sup>3</sup> at station 10 (Cemetery Kloten, 1,400m above ground) from attributable aircraft flyovers. Analyzed were heavy long-haul flights departing from Runway 16 and flying over station 10 when finally heading westwards.

### 3.5. Single event discrimination

Particle number concentrations were found to be well in line with the overall daily flight schedule on an hourly basis. When analyzing the UFP concentration – aircraft activity pattern at a fine resolution of twenty seconds, it is far less pronounced. Aircraft and vehicle activity within a distance of approx. 100m to the station 1 (Roof Pier A) and similarly to the station 2 (Meteo Garden) were logged with aircraft and vehicle traffic data and radar respectively and synchronized with the measured concentrations. Some correlations were found with a certain time delay of 1-2 minutes, but particle number concentrations were not always source characteristic and a truck would trigger a high peak with very low particle diameter (and vice versa with an aircraft). Occasional mismatches (high peaks with no activity) were observed as well and indicate the difficulty to reliably match activity events with concentrations when source and receptor are not very close.

### 3.6. Comparison to a nearby road

Monitoring station 8 (Heliport West) is located between a busy cantonal road (370m) und Runway 16 (460m). For both sources, comparable hourly activity profiles were available and were used in conjunction with particle number concentrations and size at the monitoring station. Fig. 6 shows the diurnal pattern in relation to vehicle and aircraft activity.

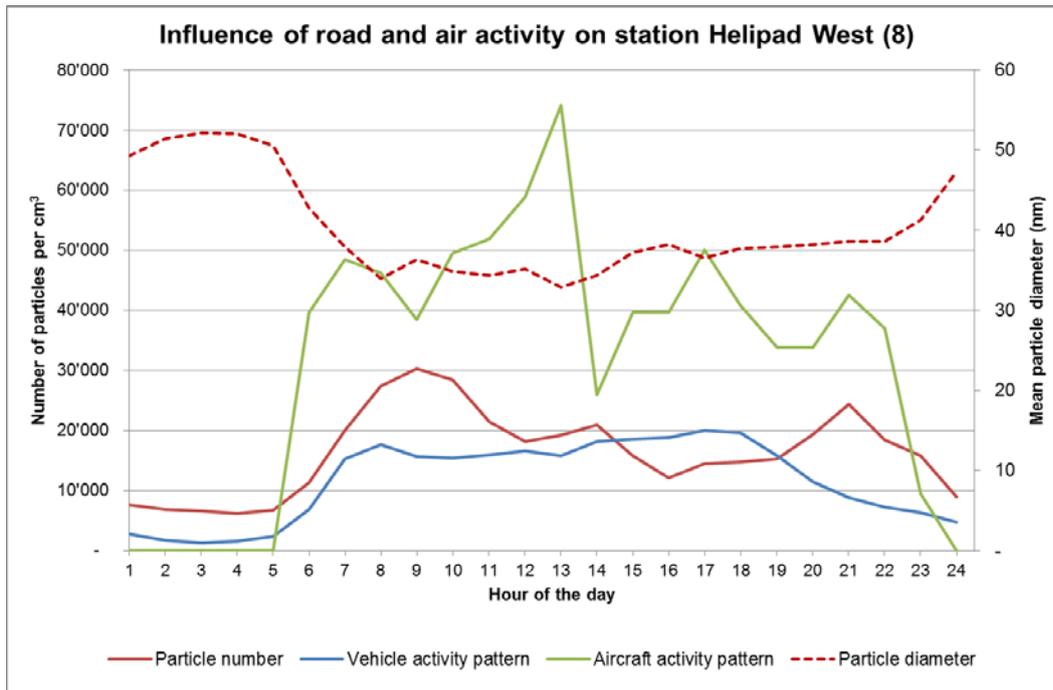


Figure 6 Diurnal particle number concentrations and size with road and aircraft activity profiles (no dimension)

The hourly particle number concentrations vary between 7,000pt/cm<sup>3</sup> at night to 30,000pt/cm<sup>3</sup> during the peak time of 08-10 o'clock. Aircraft activity peaks become not visible and the concentration pattern follows more the vehicle activity pattern. In addition, wind speed and direction have been analyzed (Fig. 7). Now the particle concentrations are much higher from the airport and increase with wind speed whereas the road dominated particle numbers remain largely the same at different wind speeds.

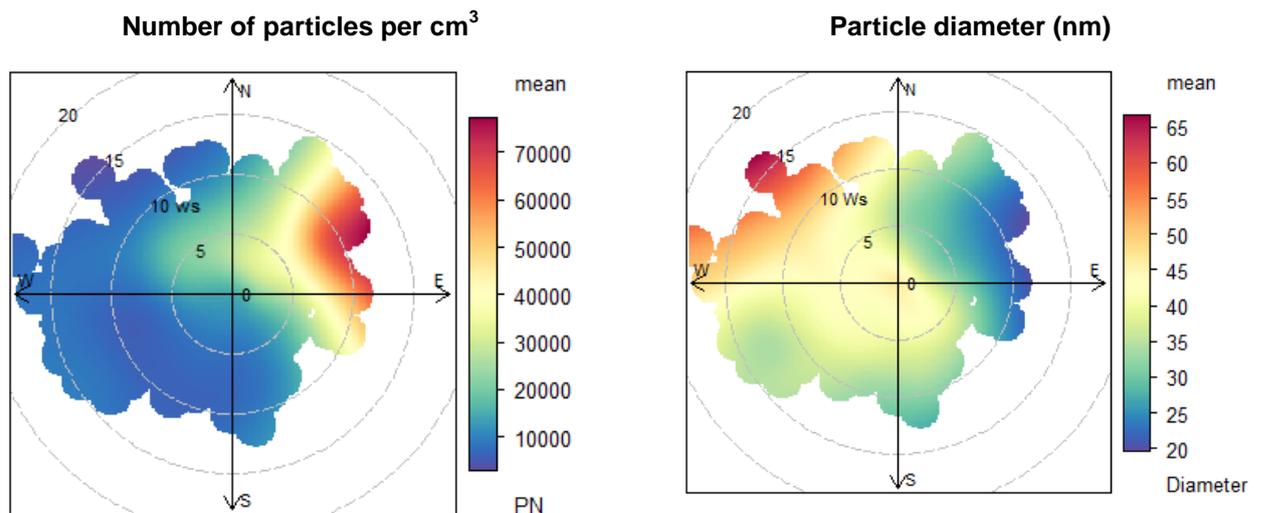


Figure 7 Polar plot of particle numbers (per cm<sup>3</sup>) and particle diameter (in nm) with wind speed (m/s) and direction at site 8 (helipad). Ws: wind speed, PN: particle number.

## 4. Conclusions

This study demonstrates the high temporal and spatial variability of UFP concentrations on the airport area, and the importance of wind speed and direction as confounders. It also shows the significant decrease of number concentrations with increasing distance from the source. Short-term measurements at single locations may drastically over- or underestimate the true (average) UFP concentrations at airports.

UFP measurement locations must be chosen carefully, should always be complemented with wind speed and direction measurements, and operated over longer periods of time to cover a representative sample of activity and weather conditions. The extremely small particle sizes observed in this study also indicate that measurement equipment must be chosen carefully.

## 5. Outlook

The correlation of activity events and concentrations measurements needs to be better assessed by reducing the source to receptor distance and improving the synchronization of the events.

Future work is also suggested to focus on the transformation of primary and secondary aerosols and the dispersion of the particles in the vicinity of the airport. Another field of particular interest is research on the volatility of particles with respect to solid and volatile particles. This would also improve the emission source distinction and respective modelling.

## Annexes

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1.1	22.03.2017	FI	Peer reviewed.

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