Ultrafine Particle Concentrations Zurich Approach Runway 14

Contents

Summary

In spring 2019, an extended measurement campaign for total ultrafine particles[1] from aviation was conducted at Zurich Airport. Using a total of 6 sensors (Partector 2) simultaneously, ground concentrations of particle numbers, diameter (10-300nm) and LDSA (lung deposited surface area) were measured in the approach path of runway 14, starting 10 km outside the airport (longitudinal profile). In a second campaign, a lateral profile was covered with five devices in a distance of 6.1 km from the runway, extending up to 1.5 km to either side of the path.

The location of the sensors was largely unaffected from other emission sources, thus covering background concentrations and potential aircraft effects. Table 1 shows the details and results of the longitudinal campaign for total particle number concentration during daytime with and without aircraft activities with an estimate of the aircraft nvPN share and the particle size during the aircraft activity time using more detailed measurements from the airport station.

No.	Station	Distance to RWY	Overflight (m/GND)	tPN daytime with aircraft	tPN daytime no aircraft	Aircraft nvPN	Diameter (nm) daytime
110	Weiach	10.3 km	529	4'870	4'630	1.1%	57
108	Stadlerberg	8.6 km	257	4'340	3'400	4.5%	62
103	Neerach	6.1 km	371	7'110	6'930	0.5%	44
102	Höri	3.4 km	222	11'930	8'190	6.6%	32
101	Niederglatt	1.8 km	111	24'170	8'220	13.9%	20
2	Meteogarten	0 km	0	26'290	22'680	2.9%	21

Table 1 Mean of v+nvPN and weighted diameter, all longitudinal stations (rounded)

The longitudinal campaign results show that effects of particle emissions from landing aircraft can be seen up to a distance of approximately 6 km away from the touchdown on the runway, or an overflight height of up to approximately 300 m/ground. This finding is in line with observations from other gaseous substances like NOx.[2] Further away or higher, emissions tend to show no direct effects anymore.

While the sensors counted all types of particles (total particle number), the fraction of the non-volatile particles (soot particles) are also of interest. Soot particles smaller than 60nm are more directly related to combustion sources like gas turbines. An extended data analysis approach had to be applied to establish an estimate of the non-volatile particle number contributions from aircraft. Initial results show a fairly low share of 2% at a distance of 10km, rising to 14% shortly before touchdown.

Within the area of measurable effects, emissions descend to ground at a speed of less than 1 m/s, thus being much slower than e.g. wake vortices which in return don't trigger recognizable emission spikes.

However, on all stations and measurements – longitudinal and lateral – the effects of the wind are highly dominant. Direct correlations between emissions and aircraft activity can only be established at calm wind situations (<2m/s) and usually at stable atmospheric conditions (low turbulence) that can mostly be found in the mornings. Then it is possible to detect signals under the approach path and – when close enough to the runway – even attribute them to aircraft overflights. Stronger winds immediately lead to a shift and additional dispersion of the exhaust gases from the aircraft.

[1] total"(tPN) means the sum of volatile (vPN) and non-volatile particles (nvPN) number concentration or size distribution measurement. Volatile particles are formed from condensable aerosols. Non-volatile particles are solid particles, predominantly consisting of soot particles.

[2] Eurocontrol: Airport Local Air Quality, Sensitivity Analysis Zurich Airport 2004, EEC/SEE/2006/003

1. Introduction and Aim of Study

At an airport, local air quality is often an issue. Thus, airport operators strive to assess and understand local concentrations of air pollutants in an effort to reduce them.

To this end, Zurich Airport has conducted a study to examine the effects from ultrafine particle emission on ground concentrations from landing aircraft under various meteorological conditions. Of particular interest are vertical and horizontal movements of emissions from aircraft and the possible detection of single overflight events.

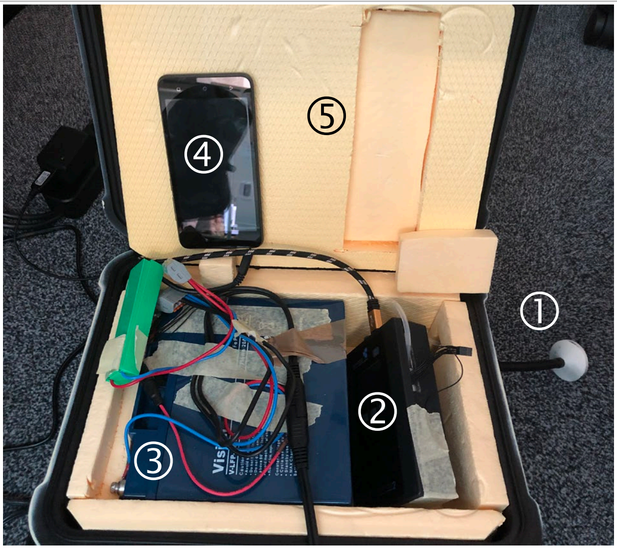
This study complements a previous campaign in 2016, where ultrafine particle concentrations were assessed simultaneously at several stations within the airport perimeter plus one background station downwind the airport[3].

The study does not claim to be exhaustive in all details. It is based on a limited number of measuring devices and for a limited campaign duration.

2. Study Methodology

2.1. Measurement Device

The measurement device used for the campaign was a Partector 2[4]. It is characterised by the compact size and the possibility to run on battery power for a longer period of time.



Partector 2:

- Particle number range: 0 – 10^6 /cm^3
- Particle size range: 10 – 300 nm
- Particle type: volatile and non-volatile
- Measurement frequency: 1 Hz

Substances

- Particle number (10-300nm)
- Average particle diameter
- LDSA (Lung Deposited Surface Area)
- UFP mass (PM 0.3)

Figure to the left:

1. Inlet (with a drop stop)
2. Partector 2
3. Battery Pack
4. Mobile Phone (for data transmission)
5. Case

Figure 1 Partector 2 in the protection case

[3] Flughafen Zürich AG (Fleuti, Maraini, Bieri; Fierz [FHNW]): Ultrafine Particle Measurements at Zurich Airport, 2017

[4] See: http://www.naneos.ch

2.2. General Study Set-up

The campaign has been structured in two parts, whereas the first part included a “longitudinal” campaign and the second part a “lateral” campaign thereafter. Considering the known very high spatial and temporal variability in UFP concentrations, six and five identical devices were used simultaneously in various locations (table 2, figure 2 and Annex 1). All devices were tested and calibrated before the campaign and a one week test campaign was run prior to the actual measurements in order to test the reliability of monitoring and data transmission. Due to the different measurement techniques, it was considered important to use identical and calibrated sensors in order to directly compare the measurement results.

Parameter	“Longitudinal”	“Lateral”
Duration	27.03. - 14.04.2019 (2.5 weeks)	24.04. – 05.05.2019 (1.5 weeks)
Number of sensors	6	5
Max distance (km)	10.3 (to Runway threshold)	1.5 (to path centerline)

Table 2 Study Parameters

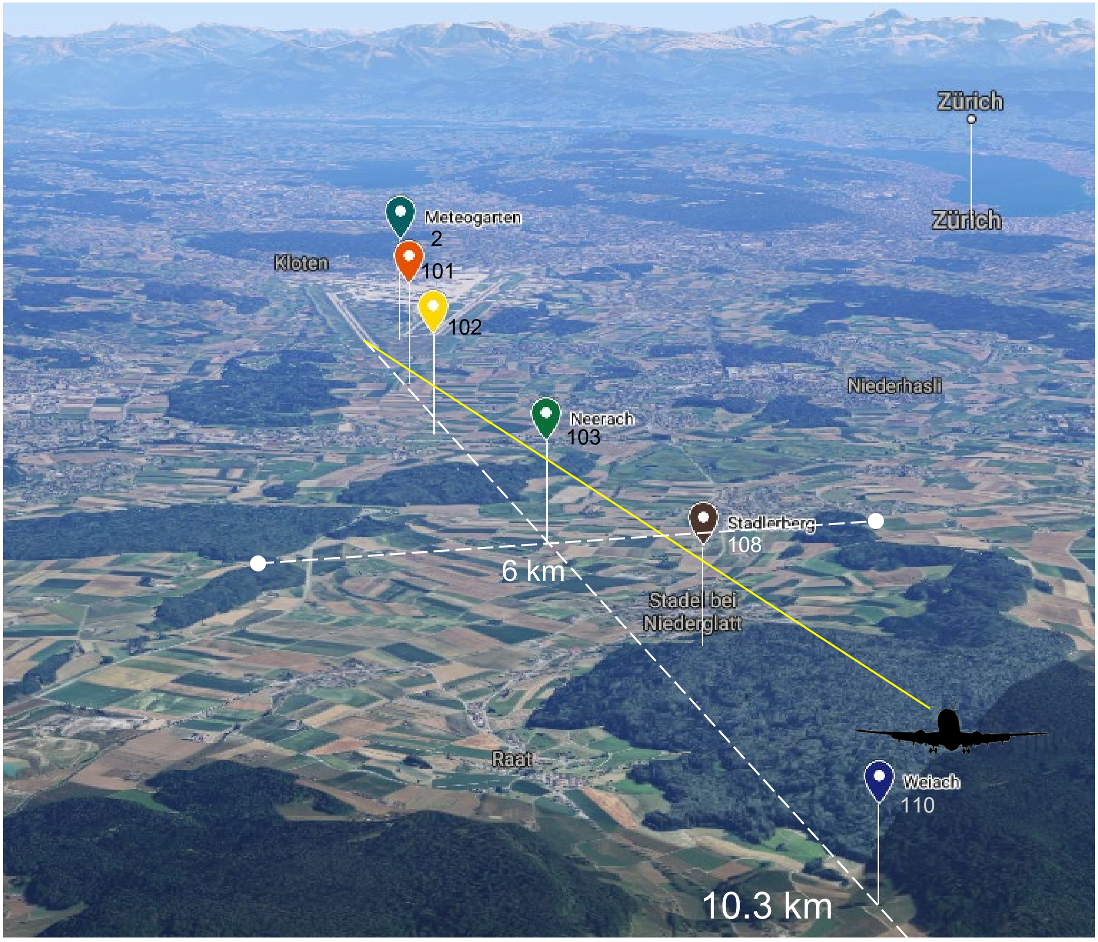
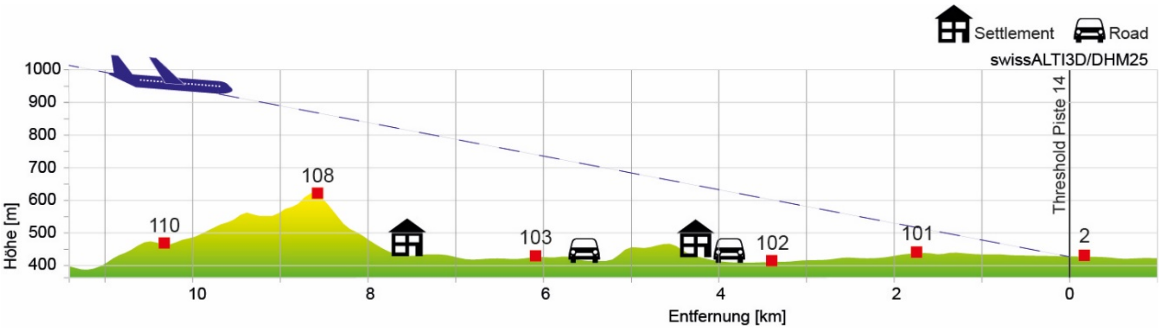


Figure 2 Aerial View of Monitoring Sites (see Annex 1 for detailed map)

2.3. Measurement Layout "Longitudinal"

The actual layout and geometry of the six measurement devices is depicted in figure 3.



Station	110	108	103	102	101	2
Name	Weiach	Stadlerberg	Neerach	Höri	Niederglatt	Meteogarten
Distance to RWY	10,340m	8,570m	6,085m	3,395m	1,800m	0m
Elevation (ASL)	467m	623m + 30m	427m	411m	438m	421m
Flight altitude (ASL)	996m	910m	798m	633m	549m	0m
Overflight (GND)	529m	257m	371m	222m	111m	0m

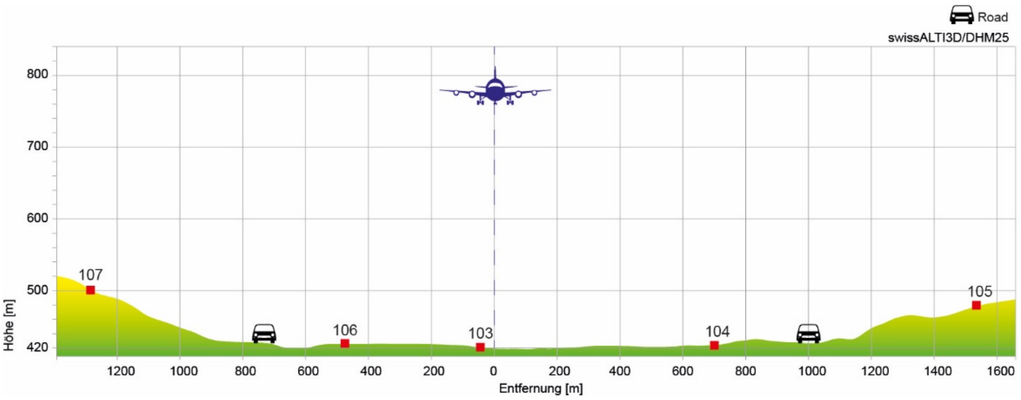
Figure 3 Longitudinal terrain profile from 10.3 km to touchdown Runway 14

In an effort to avoid influences from potentially high background concentrations, the devices were placed away from human activities as far as possible (figure 4, several examples), Power was usually provided by internal battery (up to two weeks), a solar panel or in one case external mains power.

Figure 4 Images of selected sensor locations (longitudinal campaign)

2.4. Measurement Layout «Lateral»

Similarly, the layout of the “lateral” campaign included five devices, symmetrically placed on either side under the approach path, using Station No 3 (Neerach) with a longitudinal distance of 6,085m to the runway threshold as the midpoint under the approach path (figure 5).



Station	107	106	103	104	105
Name	Stadel Binzrüti	Stadel Hau	Neerach	Hochfelden	Rotenbrunnen
Distance to center path	Ca. 1,300m	Ca. 500m	0m	Ca. 710m	Ca. 1,500m
Overflight (GND)	281m	355m	371m	326m	285m

Figure 5 Lateral terrain profile at 6 km distance to runway 14

Figure 6 Images of selected sensor locations (lateral campaign)

2.5. Meteorological Conditions

The measurement campaign was dominated by a lot of weaker winds from the NW (mostly <5 m/s) and fewer, but stronger winds from the NE (<10 m/s, frequency plot figure 7). There were also phases of calm wind (i.e. <2 m/s) that were used to evaluate the measurements.

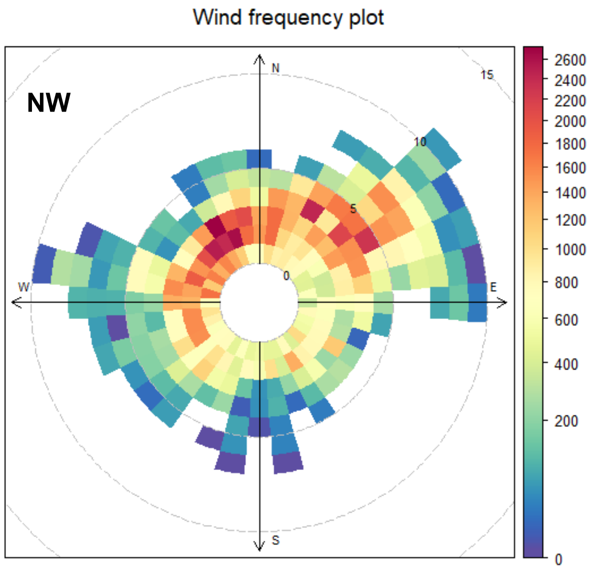


Figure 7 Wind frequency plot during the measurement campaign

Temperatures ranged from 8°C to 15°C during daytime and dropped to -5°C to 1°C during night time. There was only one significant rain event with precipitation of 5mm/min (figure 8 for the longitudinal campaign).

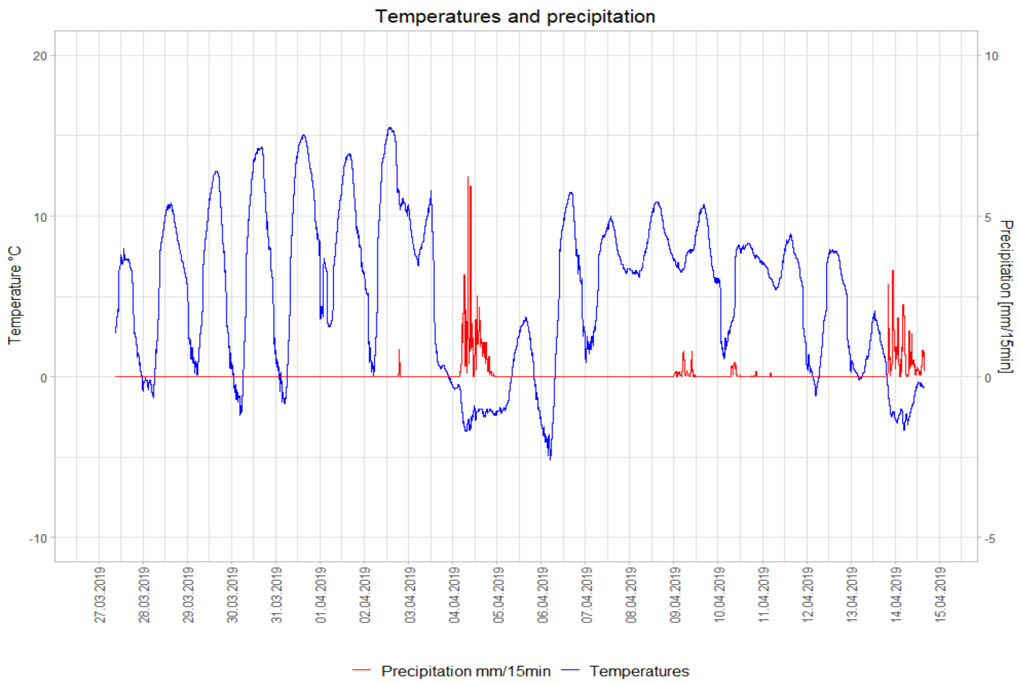


Figure 8 Temperatures and precipitation during the longitudinal campaign

3. Results of Longitudinal Measurements

3.1. General Results

Figure 9 shows the overall results of the campaign and all stations, including the wind velocity (top).

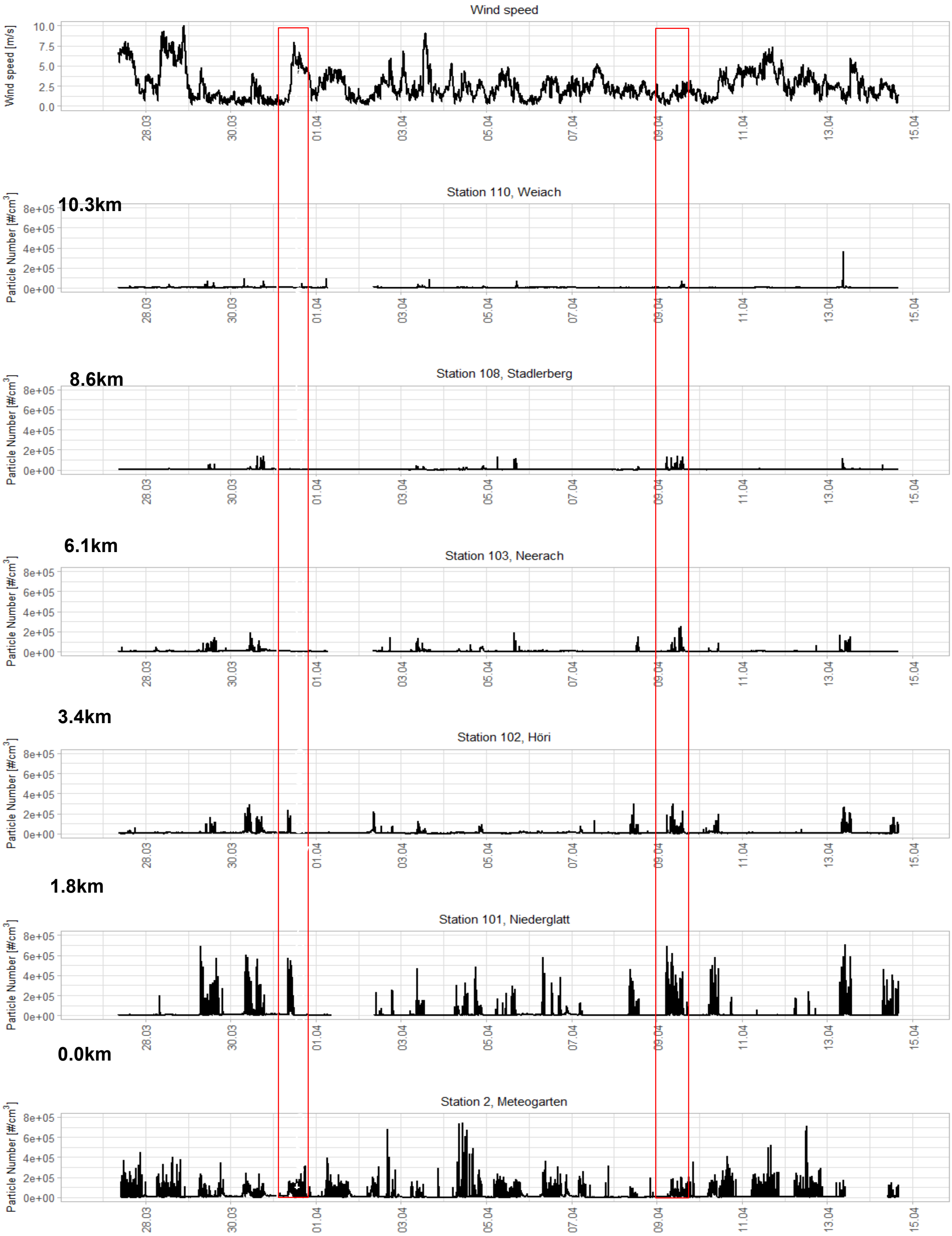


Figure 9 Hourly mean number of total UFP/cm³, all stations (longitudinal campaign)

It starts at station 110 (the furthest away) and ends at station 2 (at the airport). The results are hourly mean values over the whole longitudinal measurement period with the same scale (0-800,000 #/cm^3). The results visually demonstrate the general trend of decreasing impact with distance and thus increasing aircraft altitude. At stations 103, 108 and 110 only scattered peaks become apparent, while stations 2, 101, 102 show more and distinct phases of higher particle concentrations. While every effort was made to place the stations away from ground based activities, some results may still be influenced by non-aircraft emissions.

The variability of concentrations can distinctively be seen on 31.03. with stronger winds (5-8 m/s) where stations 101 to 110 show hardly any concentrations and 09.04. with calm and low winds (<2.5 m/s) where low concentrations can be seen at station 110 that increase with decreasing distance to the airport up to station 102. This can be attributed to the wind, where even low wind speed transport the particles away from the station.

The comparison of the measurements between stations 2 (at the airport) and station 101 (1,8 km distance, 111m overflight) show that often the further distant station has higher concentrations. There are two reasons for this: First, the aircraft is still under approach configuration over station 101 and the engine power is above idle, whereas near station 2, the aircraft is flaring and engines are completely at idle. Second, the measurement station 101 is directly under the flight path, whereas station 2 is approximately 200m away from the runway centerline. This demonstrates again the high spatial variability of concentrations.

3.2. Concentrations during and without aircraft activities

The measurements were further evaluated for periods of aircraft activities (landings Runway 14) and other times of the day. Table 3 shows the two time slots (07:00-21:00 each with and without aircraft activity and 00:00-05:00 with no activity). The emissions during 00:00-05:00 can be considered as low background concentrations. However, the values are likely conservatively low, as all emission sources are less active during the night time than during day time.

No.	Station	(v+nv) Particle Number [#/cm3]			(v+nv) Particle diameter [nm]		
		07-21 with aircraft	07-21 no aircraft	00-05 no activity	07-21 with aircraft	07-21 no aircraft	00-05 no activity
110	Weiach	4'870	4'630	4'080	56	64	69
108	Stadlerberg	4'340	3'400	3'760	61	77	73
103	Neerach	7'110	6'930	4'930	44	46	66
102	Höri	11'930	8'190	6'030	32	42	58
101	Niederglatt	24'170	8'220	5'960	20	43	62
2	Meteogarten	26'290	22'680	7'030	21	29	54

Table 3 Mean of v+nvPN and weighted mean diameter, all stations (rounded)

The values for the first three stations at 10.3 km, 8.6 km and 6.1 km (110, 108 and 103) show very little differences between phases with and without aircraft activity. It's only at station 102 (distance of 3.4 km and 222 m overflight) that particle numbers increase and their diameters decrease during times of aircraft activity. This gets more pronounced closer to the runway and shows a maximum at station 2 (touch-down of aircraft). Particle number concentrations during the night-time are generally low and only gradually increase towards the airport (figure 10).

The high particle number value at Station Meteogarten, 07-21, no aircraft, would need further analysis. A possible explanation is that this station is close to Runway 16 (400-450m) and may thus also capture all of the long-haul departures during the day plus other on-site activities and not just the arrivals on Runway 14. The "no aircraft" would thus only indicate "no direct Runway 14 aircraft activity", but would already include all other emissions from the airport.

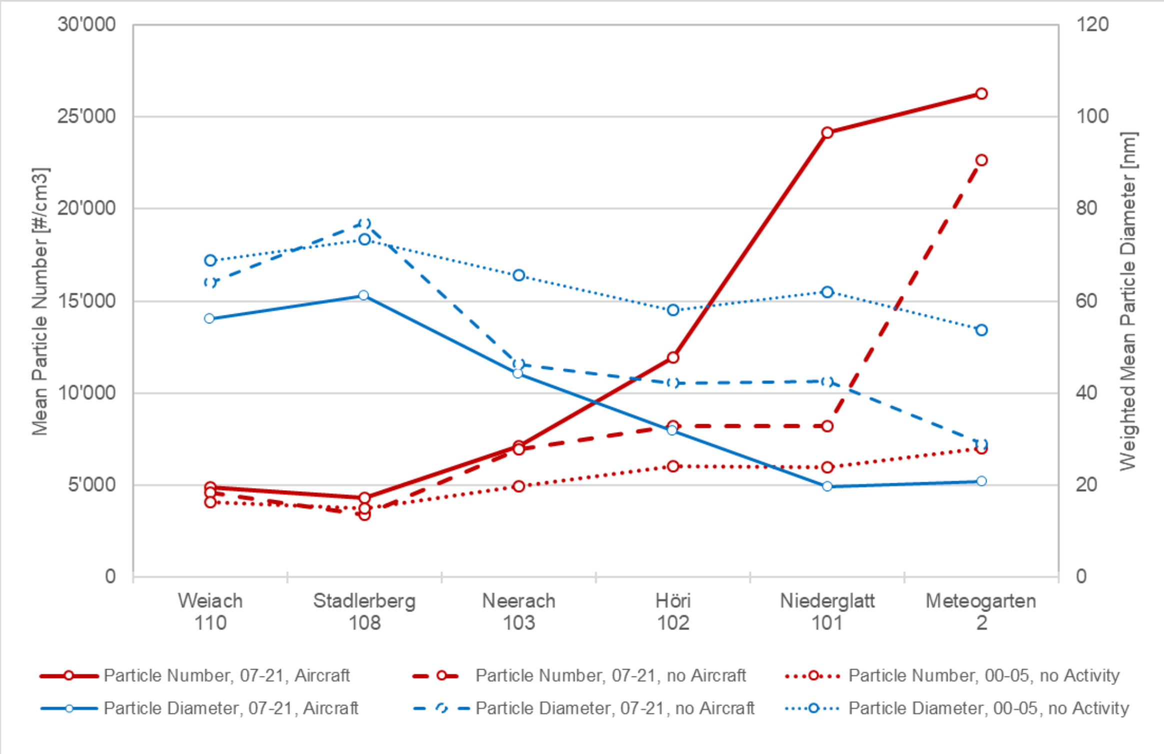


Figure 10 Mean particle number and size in daytime (with/without aircraft activity) and during night-time

3.3. Effects of various wind situations

The influence of wind on the mean particle numbers and diameters is dominant at the airport itself.[5] Additionally, also in the vicinity of the airport, the wind situations (wind speed and direction) are significant for the measured particle numbers and sizes on the ground underneath the overflight.

The following figure shows two of the monitoring stations (101 and 103) with their diurnal mean particle number concentrations (15min-values) and average diameter during specific wind situations: Calm wind (< 2m/s) and side wind (>2 m/s). This side wind can be from either side and is only to demonstrate a determined horizontal shift of the air. At the same time, the aircraft activity is displayed – for the corresponding wind situation – with overflights for landings on Runway 14 following the approach path.

[5] Flughafen Zürich AG (Fleuti, Maraini, Bieri; Fierz [FHNW]): Ultrafine Particle Measurements at Zurich Airport, 2017

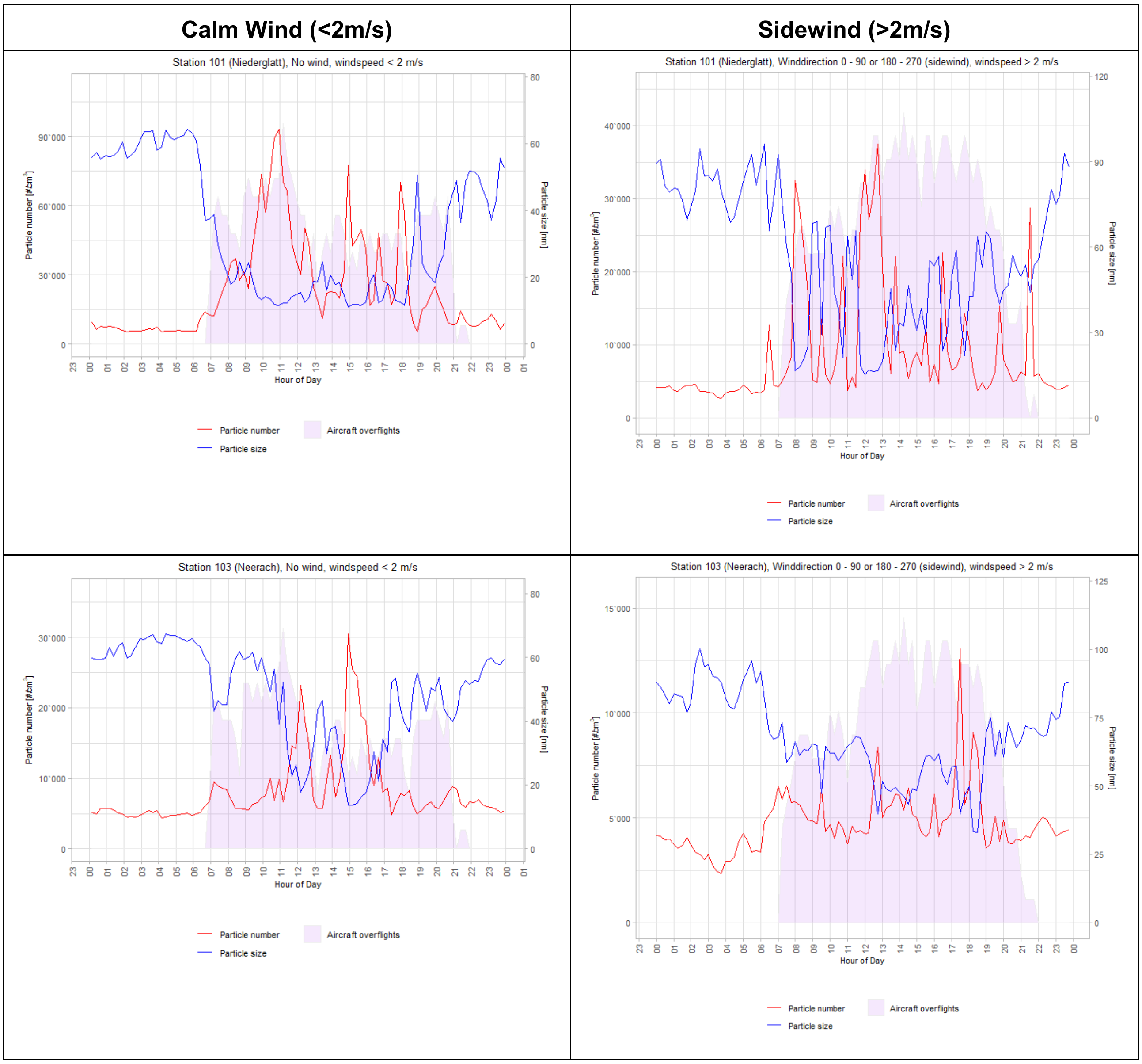


Figure 11 Correlation of different wind situations with particle numbers and diameter at two stations

At station 101 (Niederglatt, 1.8 km), particle numbers range from 15,000 particles to 45,000 particles and a few spikes up to 90,000 particles during aircraft activities and calm wind situations (<2 m/s). Also, the particle number pattern tends to follow the activity pattern to a certain degree. With side wind >2 m/s – and from either side –particles number range only from 5,000 to 25,000 particles with spikes to 37,000 particles. Additionally, there’s little correlation between particle numbers and activity profiles.

At station 103 (Neerach, 6 km) this picture is very similar with particle numbers ranging from 5,000 to 15,000 particles (spikes to 30,000) during calm wind and then particles numbers from 3,000 to 8,000 particles (spikes to 13,000) during side winds of >2 m/s and aircraft operations. There’s already less correlation between measured concentrations and the activity profiles.

3.4. Identification of individual aircraft emissions

An effort was made to try and identify and characterize single aircraft events in the measured data. This analysis also required the consideration of the potential time delay between an observed overflight and the detection of a distinct signal on the sensor. Unlike for instance noise emissions, gaseous emissions have a much lower horizontal and vertical dispersion speed over time, depending of course on the wind speed and the atmospheric turbulence. So the signal strength and thus the ability to attribute it to an event depends on the overflight height of the aircraft, the amount of emissions and the wind conditions.

Initial analysis showed that the stations 110 (Weiach) and 103 (Neerach) were found to be overflown at too high an altitude to detect an attributable signal, and only the stations with an overflight height of 111-257 m yielded usable results.

To this end, the station Niederglatt (No 101, 1,8km to runway, 111m overflight) was further analyzed, selecting a 60-minute timeslot at the beginning of the daily aircraft activity for two wind situations. In figure 12, the overflights are all labelled with time and aircraft type.

The first situation with calm wind from NW (<2 m/s) shows the first spike appears approximately 2.5 minutes after the first overflight. Spikes then occur irregularly thereafter, however not correlated to overflights anymore, even if a certain time delay is considered. The height of the spike also does not correlate to the size of the aircraft. An Airbus 220 (BSC3) may trigger a higher spike than a Boeing B777 (B77W) if the wind situation is adverse or the emissions are more diluted.

Looking at a second wind situation with stronger NE winds of 4-6 m/s, there are no spikes detectable anymore, despite the recorded overflights. The wind has dispersed and shifted the emissions away from the station on the ground.

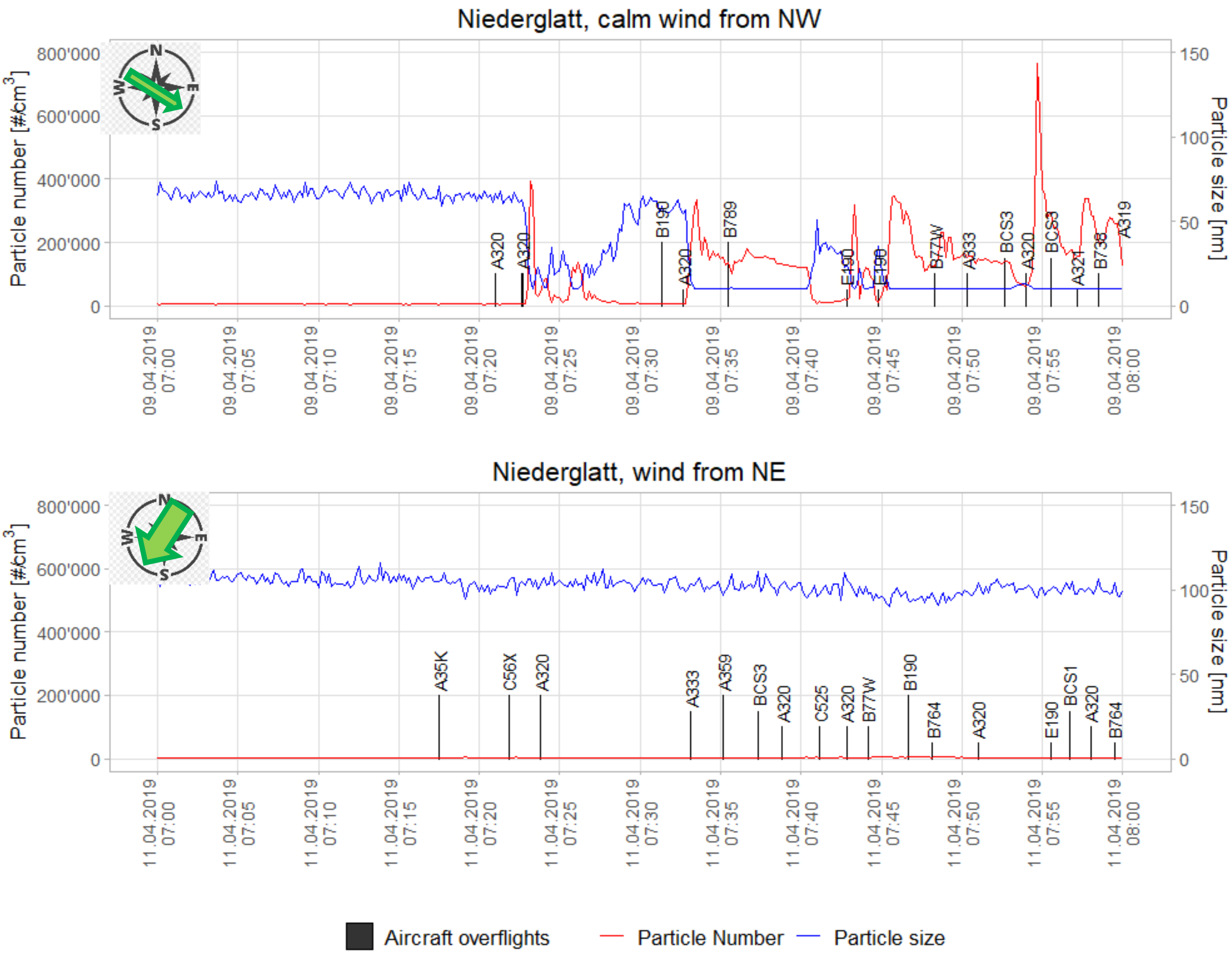


Figure 12 Single event analysis Station Niederglatt (101, 1.8km to runway, 111m overflight)

The initially observed time delay of 2.5-3 minutes between overflight and sensor signal was further analyzed using other stations with lower overflight heights. The three stations 101, 102, 108 with overflights at 111-257 m were analyzed for the first morning flights during calm wind conditions.

Figure 13 shows the time delay in relation to the overflight height. The linearity of the results suggests a good correlation between height and time, with a vertical dispersion speed of approximately 0.7 m/s.

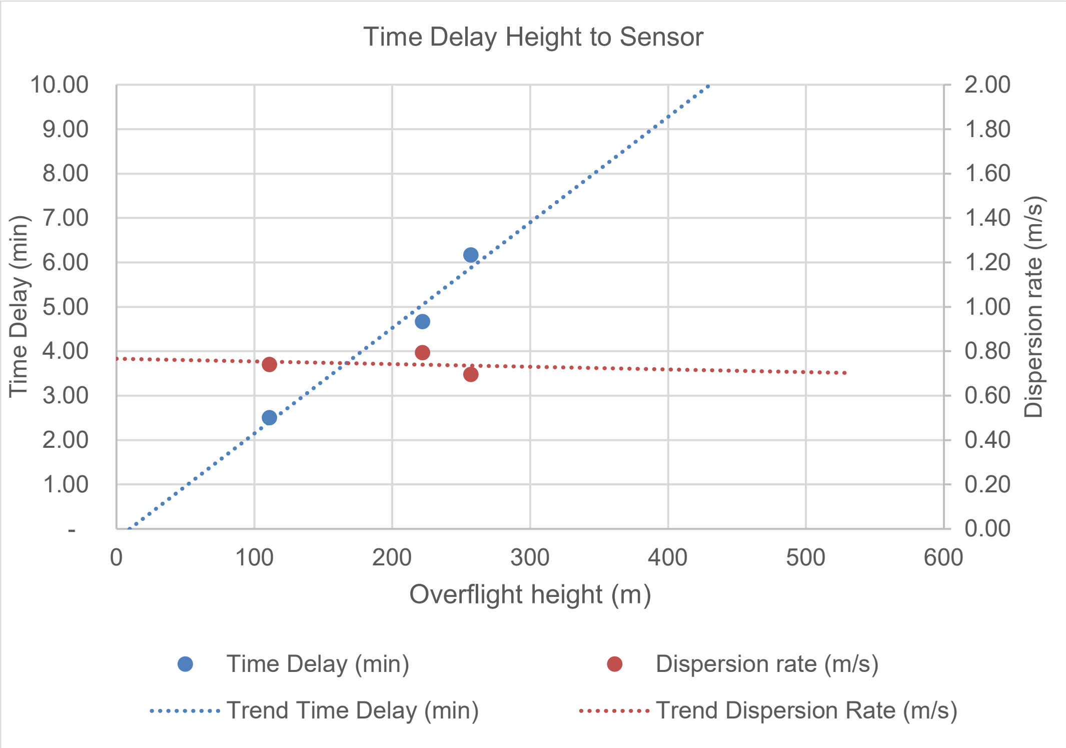


Figure 13 Time delay of overflight to sensor signal during calm wind conditions

3.5. Average particle size analysis

To determine particle size distributions, usually the use of a more advanced device is required (e.g. a SMPS). The devices used for this campaign only deliver the mean diameter of the particles measured. This means that a value of e.g. 35nm is an average consisting of particles ranging from 10-300nm. However, the lower the mean diameter value is, the more small particles this value actually contains. As such, an approximation for the particle size analysis has been used by analyzing the mean particle size and their respective numbers over the measurement period.

Figure 14 shows the size distribution of particles for three of the stations: the most distant one (No. 110, 10.3 km), the closest one (No. 2, 0m) and one in between (No. 102, 3.4km). As expected, the Meteogarten station (2) shows the highest particle numbers at the smallest average sizes of 15-20 nm with continually decreasing numbers with increasing size. Station Höri (102) is initially similar, but shows a second peak around 40-50 nm. Station Weiach (110) finally still has high numbers at small diameters, but shows even higher particle numbers at diameters of 60-70 nm.

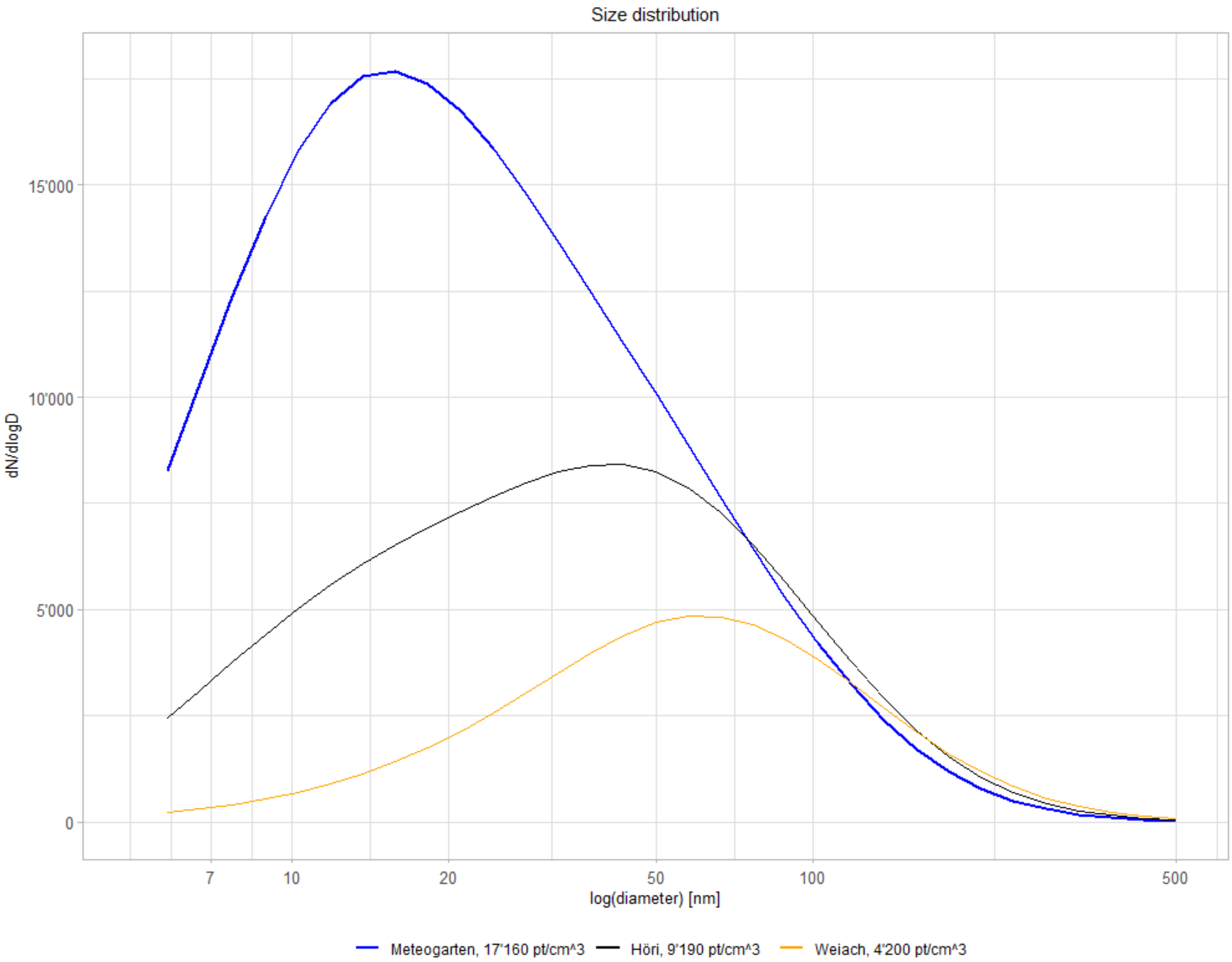


Figure 14 Approximation of particle size distribution at several stations

4. Results of Lateral Measurements

The lateral measurements were done to assess to what degree side winds affect the particle number concentrations on the ground and how such air parcels are being shifted. Over a lateral transect at station 103 (Neerach, 6 km from the runway), five devices were placed at symmetrical distances to the overflight path. The distances were chosen to be on either side first twice the overflight height of 371 m (resulting in +/-650m) and then four times the heights (resulting in approx. 1.5 km).

Three different wind situations were assessed both for phases of aircraft activity (overflights for landings on Runway 14) and without any activities over the full lateral measurement period. Figure 15 shows the lateral total particle number concentrations and diameters at calm wind conditions (≤2 m/s). During aircraft approach activity, the highest concentrations can be observed directly under the approach path, with concentrations decreasing to either side of the path. During times with no aircraft activity, concentrations are largely the same across the profile.

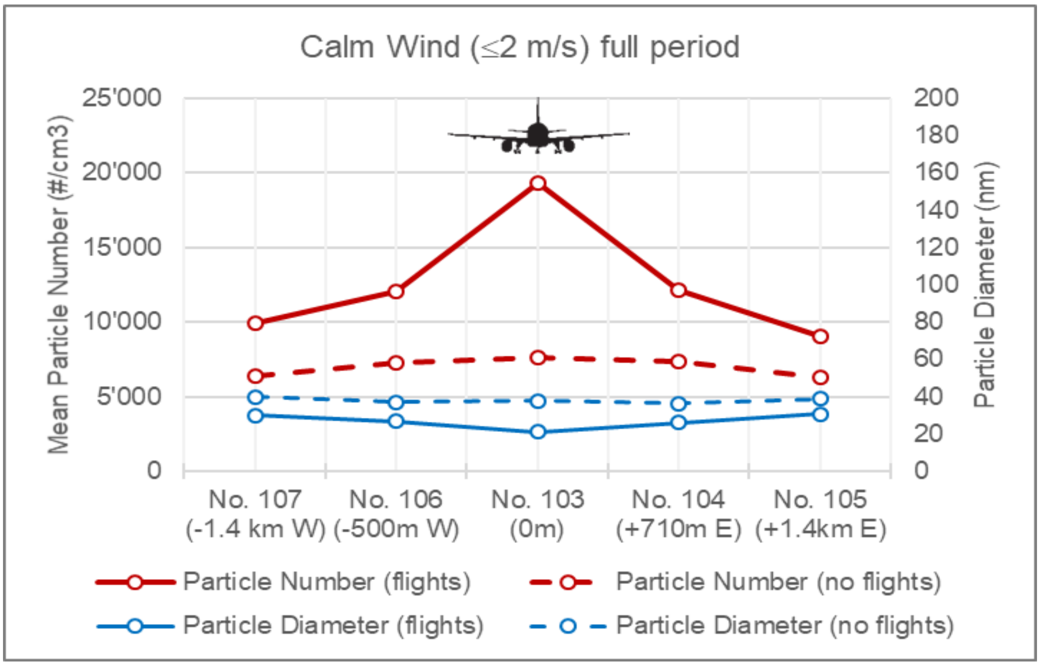


Figure 15 Lateral total particle number and size profile under calm wind conditions

The prevailing wind direction near the airport is West to South-West. Figure 16 shows two situations with predominant Westerly wind. One situation (left) shows the concentrations as an average over the full lateral measurement period. In this case, there is no distinct peak under the approach path detectable. Instead, the concentrations are more shifted to the East. During the times with no aircraft activity the profile shows a similar shape, just with generally lower concentrations and decreasing again with increasing distance to the East.

The other situation (right) shows just a very specific short time period of a few hours on a specific day with West-Southwest wind of approx. 3.9 m/s. In this case, concentrations increase downwind of the aircraft approach path. Due to the site layout, the maximum offset cannot be determined and seems to be ≥1.5 km distant to the approach path. However, only selected and specific short-term situations show the expected increased downwind concentrations. Only longer-term measurements might indicate a generally applicable trend well enough.

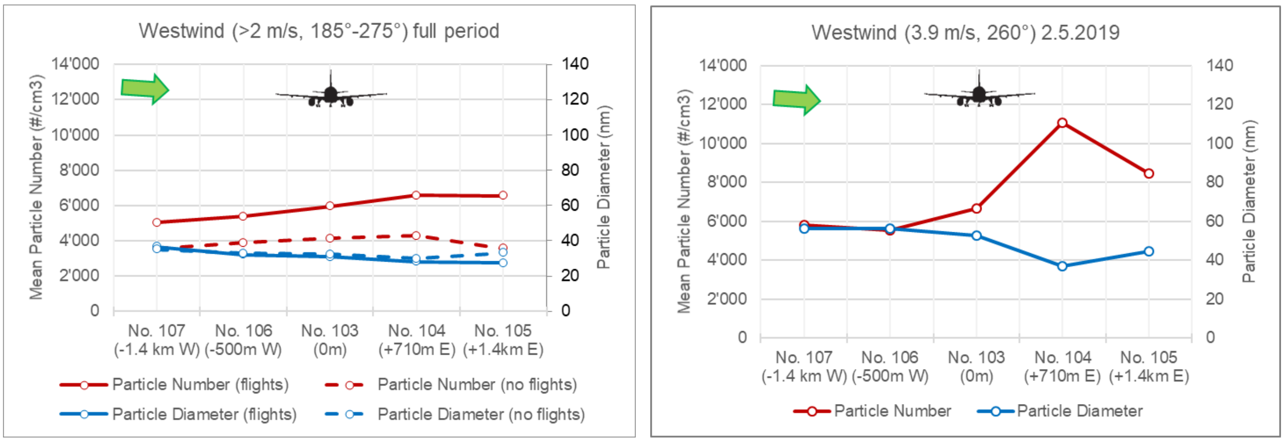


Figure 16 Lateral particle number and size profile under two Westerly wind conditions (green arrow)

The opposite wind situation is Easterly wind, however less frequent. Again the full duration measurements only show a moderate increased downwind concentration in Figure 17. Likewise to the Westerly wind situation, a short and selected situation with Easterly wind of 2.5 m/s over several hours shows an increase on the particle number concentrations downwind the approach path. The general peak in the area of Station 104 may be attributed to the nearby city of Bülach (see Annex for regional map) where particle emissions could be shifted from, while Station 105 is more shielded by a forest.

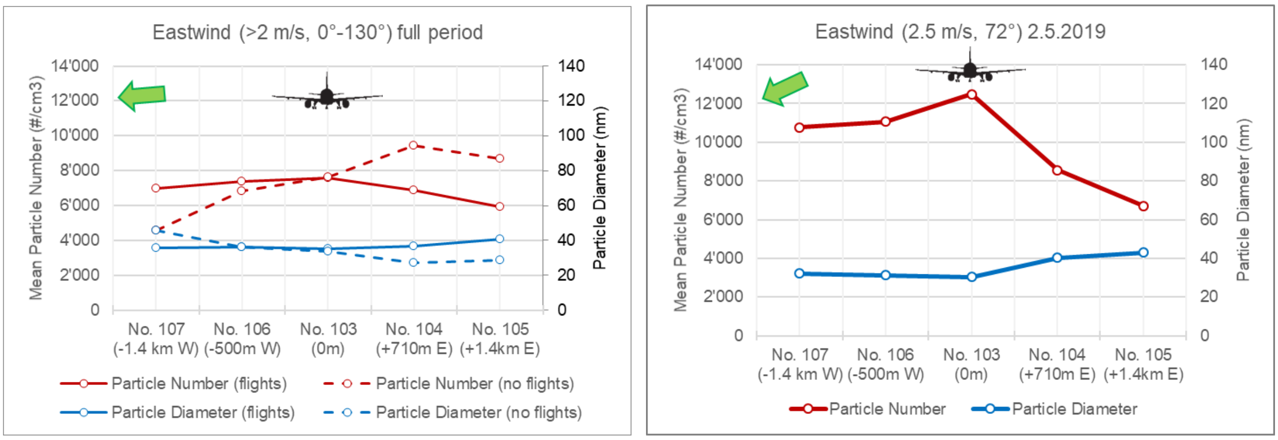


Figure 17 Lateral particle number and size profile under two Easterly wind conditions (green arrow)

5. Determination of Non-volatile Aircraft Particles

One of the challenges associated with measuring the concentrations of substances lies in the missing source discrimination. The measurement device captures the ambient concentration originating from different sources plus the existing background. This is also the case for UFP concentration measurement.

The particle size is an indicator to determine the share of aircraft related particles in the air. However, this would firstly require the use of measurement device with a particle size classifier (e.g. SMPS) and secondly still doesn't address how to handle the size range where particle sizes overlap from different sources. In an effort to single out concentrations from overflying aircraft, a multi-step approach has been used as a surrogate in this campaign:

1. The mean particle concentrations were measured during the time of actual and relevant aircraft activity, which is basically the time from 07:00-21:00 (weekdays), slightly less during weekend and none if the wind conditions prevent the use of this runway. Specifically, each overflight plus the first 10 minutes thereafter is considered and only results with wind speeds of less than 5 m/s.
2. The mean particle concentrations were measured during the time with no aircraft activity, but activities of all other sources. Specifically, the times between overflights are considered again from 07:00-21:00 and wind speeds of less than 5 m/s.
3. The difference between the two mean results is considered an estimation of the aircraft contribution of total particles to the overall measured concentration, knowing that some other sources still may influence the overall results.

The concentrations derived are the total particle numbers, i.e. the sum of the volatile and non-volatile particles. As the number of the non-volatile particles (nvPN) are of special interest, an assessment has to be made for the split between volatile and non-volatile particles. Soot particles smaller than 60nm are more directly related to combustion sources like gas turbines. Additionally they are in the focus for their potential adverse health effects. In this case, the measurements of the permanent UFP monitoring station at Zurich Airport has been used. This U-SMPS counts and measures the total and non-volatiles particles simultaneously on the roof of Pier A. The effects of varying percentage due to ageing of particles and the increasing distance to the actual emission source could not be considered in this study. Instead, this basic percentage has been used.

4. The average percentage of non-volatile particles to the total calculated which was 21% during the measurement campaign was applied, thus receiving the average non-volatile particle number concentrations from aircraft activity (figure 18). It is understood that the percentage on non-volatile on the total particle numbers varies depending in source proximity, time elapsed and ambient conditions and is still an estimate due to potential particle losses in the catalytic stripper. In the absence of more detailed data, the derived average has been applied to all stations.

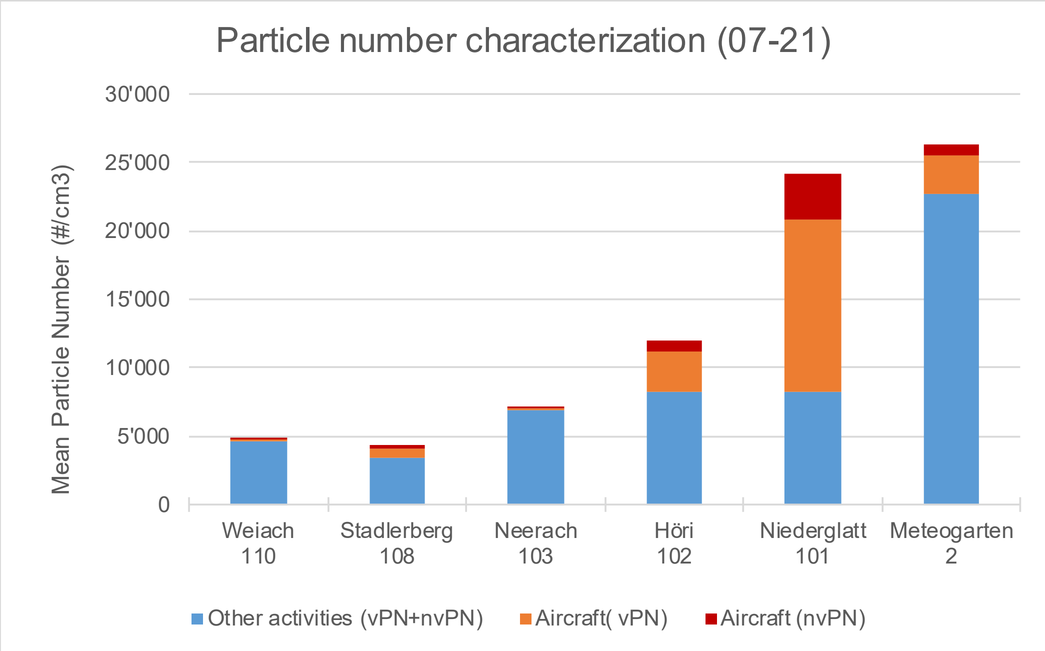


Figure 18 Particle number source characterization at measurement stations along Approach 14

The aircraft non-volatile particle number contributions to the total measured particle number for all the stations is listed in table 4.

Stn.	**110**	**108**	**103**	**102**	**101**	**2**
Name	Weiach	Stadlerberg	Neerach	Höri	Niederglatt	Meteo-garten
Aircraft nvPN	1.1%	4.5%	0.5%	6.6%	13.9%	2.9%

Table 4 Share of estimated aircraft nvPN on total measured particle number

The results at the two stations Niederglatt (101) and Meteogarten (2) in figure 18 may require additional analysis or a larger set of measured data. However, the following aspects have to be considered:

- The station Niederglatt is directly below the flight path (111m, no lateral offset) and the aircraft engine setting is still at an average “approach” setting, with many and sudden engine thrust changes to maintain a stable approach on the glide path. In Meteogarten, the aircraft has reached the touch down zone (with a lateral offset of 180m from the runway centreline) and is flared with engines completely at idle.
- The station Meteogarten is in the proximity of Runway 16 (400-450m) and may thus capture emissions from all long-haul departures.

6. Conclusions and Outlook

The longitudinal campaign results show that effects of particle emissions from landing aircraft can be seen up to a distance of 4-5 km away from the touchdown on the runway, or an overflight height of up to approximately 300 m/ground. This finding is in line with observations from other gaseous substances like NOx.[6] Further away or higher, emissions tend to show no direct effects anymore.

The sensors counted all sorts of ultrafine particles (total particle numbers). In order to estimate the non-volatile particle number contributions from aircraft, an extended data analysis approach had to be applied. Initial results show a fairly low share of 1% at a distance of 10km, rising to 14% shortly before touchdown. This would have to be further explored.

On all stations and measurements – longitudinal and lateral – the effects of the wind are highly dominating. Direct correlations between emissions and aircraft activity can only be established at calm wind situations (<2m/s) and usually at stable atmospheric conditions (low turbulence) that can mostly be found in the mornings. Then it is possible to detect signals under the approach path and – when close enough to the runway – even attribute them to aircraft overflights. Stronger winds immediately lead to a shift and additional dispersion of the exhaust gases from the aircraft.

The lateral displacement of emissions could not fully be measured due to the limited spatial placement of the sensors. To this end, it is not yet established how far out emissions are transported that could be assigned to aircraft activities or likewise, how far airport emissions that include aircraft emissions at and close to the ground are displaced into the region.

While this study focused on the emissions from the approach, possible effects from departing aircraft have not been studied. Landing aircraft are much lower in the vicinity of the airport and it is thus expected that departing aircraft with a high rate of ascent will show even lower contributions to the overall particle concentrations despite the higher power settings.

The study has yet again confirmed several key elements for measuring UFP from aviation:

- It is key to measure with multiple same-type non-moving sensors simultaneously at different locations. Given the variability in emission rates from engines and the meteorological conditions (wind), other variabilities from the measurement side are detrimental to the quality of the results (different measurement type devices or moving measuring locations).
- It is crucial to measure over a longer period of time in order to obtain comparable results and to identify some of the very specific characteristics of ultrafine particles (e.g. sensitivity to wind, high spatial and temporal variability, influence of other sources). We consider 2 weeks as the absolute minimum.
- Any interpolation of results spatially or temporarily are highly unsuited for the understanding of UFP.

Future studies are recommended to look at exhaust and concentration displacements downwind from the airport or generally the point of emission combined with the speciation of volatile and non-volatile particles.

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[6] Eurocontrol: Airport Local Air Quality, Sensitivity Analysis Zurich Airport 2004, EEC/SEE/2006/003

A.1. Regional Map with Monitoring Stations

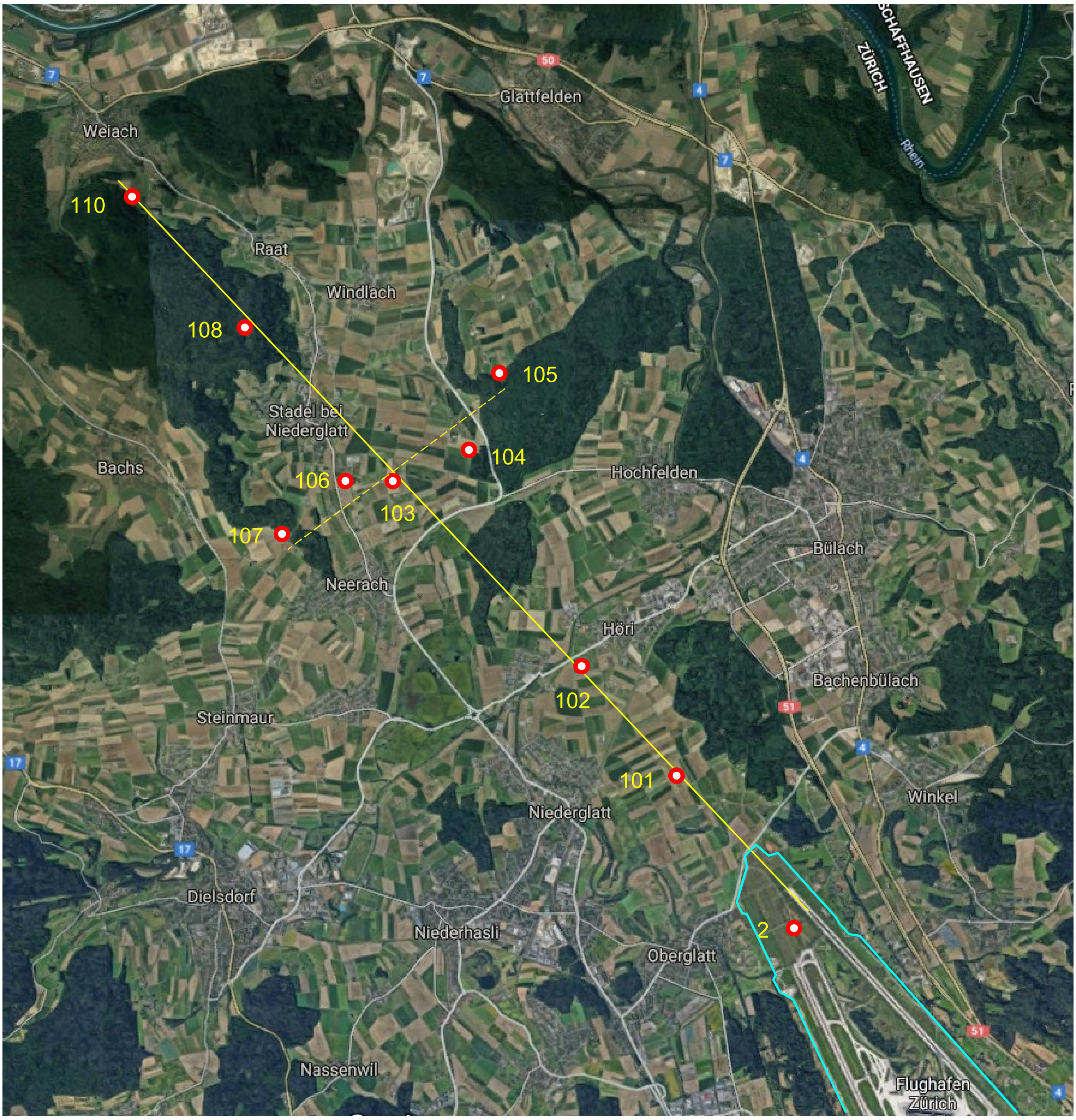

Image: Google Maps.

Figures

Tables

Abbreviations

LDSA	Lung-deposited surface area
nv	non-volatile
PN	particle number
tPN	total particle number (sum of volatile and non-volatile particles)
UFP	Ultrafine particle
v	volatile

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