Determination of the Vertical Profile of Particle Number Concentration Adjacent to a Motorway using an Unmanned Aerial Vehicle

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Abstract

A quantitative assessment of the vertical profile of traffic pollution, specifically particle number concentration (PNC), in an open space adjacent to a motorway was possible for the first time, to the knowledge of the authors, using a Unmanned Aerial Vehicle (UAV) system. Until now, traffic pollution has only been measured at ground level while the vertical distribution, is limited to studies conducted from buildings or fixed towers and balloons. This new UAV system demonstrated that the PNC sampled during the period form 10 am to 4 pm, outside the rush hours with a constant traffic flow, increased from a concentration of $2x10^4$ p/cm^3 near the ground up to 10 m, and then sharply decreased attaining a steady value of $4x10^3$ p/cm^3 beyond a height of about 40 m. While more comprehensive investigations would be warranted under different conditions, such as topography and vehicle and fuel type, this finding is of great significance, given that it demonstrates the impact of traffic emissions on human exposure, but less so to pollution within the upper part of the boundary layer.

Keywords: Vertical pollution profiles, particle number above the road, UAV and air quality, urban air pollution

1. Introduction

Understanding the dispersion of pollutants emitted from urban traffic is important to better understand their impacts on human health and the environment, and to model and predict their characteristics.

The particle number concentration (PNC) in the urban background varies between 10^3 p/cm^3 and 10^4 p/cm^3, but it is up to an order of magnitude greater in the proximity of busy road, motorways

(Morawska et al. 2008). The majority of these particles are in the ultrafine size range, below 0.1 µm. The PNC has been measured as a function of distance from roads and the results have shown that they are the highest near the roads and decrease rapidly in the first few tens of meters downwind of the road. In one study carried out from 15 up to 375 m downwind of a motorway, it was shown that the PNC decreased by 50 % between 15 and around 100-150 m from the road, when the wind was blowing perpendicular to the road (Hitchins et al. 2000; Zhu et al. 2002).

While a number of studies provided assessment of ground based horizontal profile of PNC (Gramotnev et al. 2003; Gramotnev and Ristovski 2004; Morawska et al. 2008; Morawska et al. 1999; Zhu et al. 2008), both the vertical and horizontal profiles are required for meaningful dispersion modeling and assessment of the impact of traffic emissions. Studies of particle concentrations from motor vehicle emissions as a function of altitude near the surface are very limited (Altstädter et al. 2014; Brady et al. 2016; Imhof et al. 2005; Ma and Yu 2014) and mostly related to urban street canyon measurements (Hitchins et al. 2002; Kumar et al. 2008; Wu et al. 2002). In such microenvironments, measurements are limited to specific heights and positions and significantly affected by the microclimates created by the buildings (Dimoudi et al. 2013).

The dispersion of gaseous pollutants in urban canyons depends on the rate at which the street exchanges air vertically, with the above roof level atmosphere, and laterally with connecting streets (N' Riain et al. 1998). Field measurements (DePaul and Sheih 1985; Qin and Kot 1993; Xie et al. 2003) have shown increased concentrations of traffic-related pollutants on the leeward sides of urban canyons and decreasing concentrations with height above the ground, on both sides of the street. These increased leeward concentrations are due to the accumulation of pollutants locally advected by the large wind vortex that covers most of the canyon. Minor pollution hotspots might also be created in small cavities where additional recirculation

64 phenomena can take place (Vardoulakis et al. 2003). In urban canyons, PNCs was showed to
65 change significantly with height, from a maximum concentration between 1.2 and 2 m at street
66 level decreasing with height to the highest measuring point, normally on the rooftop of the
67 building. The decrease in PNCs with height in the upper part of the canyon was attributed to the
68 removal of particles as a result of air mass exchange between the street canyon and the air above
69 the buildings, while the reduction in PNC at street level (at 1 m) was proposed to be the result of
70 dilution and dry, turbulent deposition (Kumar et al. 2008). For examples the PNC was monitored
71 in an urban canyon in Italy (Marini et al. 2015) at sampling heights of 1.2, 5.4, 12.6, and 14.5 m.
72 The maximum value of PNC was found at 1.2 m and decreased with height. The vertical PNC
73 profiles on the leeward side, showed a peak at 5.4 m decreasing toward both the lowest (1.2 m)
74 and highest (14.5 m) sampling points. Measurements though were limited to a small number of
75 vertical fixed locations.
76 Permanent air quality roadside stations, somewhere present, are typically located on the
77 pavement of these busy streets, avenues or intersections, within a few meters from the roadway
78 and with sampling locations at 1.5 – 3 m height above ground (Kumar et al. 2014). While these
79 results confirm that PNC decreases with height, the use of a UAV in an urban canyon would
80 enable a more extensive and reliable measurement of the vertical distribution of traffic generated
81 pollutants, not just within the canyon but, beyond the height of the tallest building.
82 Measurement of PM1, PM2.5, PM10, carried out from a building next to a busy road in China at
83 six different fixed heights (2, 8, 19, 30, 59 and 79 m), showed that the concentrations decreased
84 60%, 62% and 80% between 2 and 79 m above the ground, respectively (Wu et al. 2002).
85 Another study in Singapore, similarly conducted from different floors of a 40 m building located
86 30 m from a traffic road identified higher values of PM 2.5 at the midfloors, compared with

87 those collected at the upper and lower floors (Kalaiarasan et al. 2009). A further example showed
88 that concentrations of fine and ultrafine particles decreased to about 50-60% from ground level
89 readings, between heights of 0 to 6 m, to full building height 24 to 33 m above the ground
90 (Hitchins et al. 2002). On the contrary, the PNC profile was proposed to be building-specific as it
91 did not have a consistent pattern (Quang et al. 2012).
92 To date, no studies have reported PNC within the atmospheric column in an open space, close to
93 urban arterial roads. However, recent advances in hexacopter unmanned aerial vehicle (UAV)
94 technology have offered a new opportunity for vertical PNC measurements. UAVs have the
95 capacity to fly close to the ground and to maintain or change direction as required. Information
96 on the three-dimensional location of the UAV can be reliably obtained by a GPS datalogger
97 while flying between fixed waypoints, which are GPS points describing the UAV position in
98 terms of latitude, longitude and altitude. In this study we customized a commercial hexacopter
99 UAV as a system to measure the vertical profile of PNC in the proximity of a motorway. Here,
100 we present the results of this study and illustrate the feasibility of using UAVs in order to make
101 such measurements. The aim of the study was not only to develop a novel measurement system,
102 but also to use the data to determine the traffic generated PNC vertical profile associated with a
103 motorway.
104

105 **2. Methods**

106 The PNC vertical profile, adjacent to a motorway was measured by mounting a PNC monitor
107 onboard a DJI S800 hexacopter UAV. The typical flight path was a vertical ascent and descent
108 above a fixed position on the ground at a distance of 30 m from the kerb of the road. This
109 position was the minimum distance from a road permitted under the law governing the flight of

UAVs in Australia. Traffic flow rate during the experiments was assessed in real time using a video camera mounted on a second UAV, a DJI Phantom 3 professional quadcopter. The wind direction throughout the measurement period was approximately from the road towards the point of measurement. Wind speed and direction, were continuously monitored in real time with a fixed Monitor weather station located 20 m further downwind from the position where the hexacopter UAV system started its vertical flight.

2.1. The Measurement Site

The measurements were conducted adjacent to the Gateway Motorway in Tingalpa, Brisbane, Australia, at coordinate 27 29'25.7"S 153 07'21.9"E, where the motorway consisted of eight-lanes, four in each of the NW-SE direction (Figure 1). Each lane was 4 m wide and the two directions of traffic were separated by a central reservation of 8 m width. There were no buildings near the measurement area which was a flat grass field with scattered bushes and trees. There was a small residential area with parkland on the eastern upwind side of the Motorway (Figure 1).

2.2. UAV platforms

The UAV (Figure S1), which was used to accommodate the PNC measuring monitor, was the S800 EVO manufactured by DJI (DJI 2014). It measures 800 mm in width and 320 mm in height and is built with composite materials. The S800 is a hexacopter, includes six propellers and weighs 3.7 kg with minimum and maximum take-off weights of 6.7 kg and 8 kg, respectively. The UAV uses a 16000 mAh LiPo 6 cell battery, providing a hovering time of approximately 20 min with no additional payload. The hovering motor power consumption is 800 W, when operating with the minimum take-off weight. Motors run in conjunction with 38 x 13 cm props,

each of 13 g. The minimum height above the ground was set to 5 m, being the permitted safe value. The maximum height was restricted to 100 m which was within the limit permitted by Civil Aviation Safety Authority . The UAV telemetry range of 2 km was adequate to cover the entire range of 5 to 100 m.

The UAV was equipped with the DJI Wookong autopilot, allowing it to receive pre-programmed flight path instructions from the ground station software. This software was installed and used with a portable laptop computer during the field measurements to allow the hexacopter UAV to be flown autonomously. The autopilot linked with the ground station software also allowed to track and check the exact location of the UAV during the flight. The ground station software enabled the UAV action to be related to a specific waypoint, including hovering time (stationary waiting, while sampling) and translating speed from one waypoint to the next. For each programmed flight, the ground station software provided an intuitive and easy to use interface where autonomous flight paths were planned, saved, and uploaded into the UAV. In addition to the specific flight paths, the software allowed for continuous, real-time monitoring of the status of the UAV during operation, along with its longitude, latitude, altitude and waypoint tolerance.

GPS data was recorded using AARONIA, a small (L/W/D: 102 x 42 x 21 mm), lightweight (88 g), standalone GPS datalogger mounted onboard the UAV. This GPS was necessary because the Wookong autopilot does not allow the downloading of GPS data. Flight speeds during this study were 1.5 and 2 m/s, depending on the flight path used.

The second UAV used in this research was the DJI Phantom 3 Professional, a quadcopter (having four propellers), designed for aerial photography and video recording. It carried a high resolution camera (Sony EXMOR 1/2.3”; Effective pixels: 12.4 millions) and was smaller than

155 the S800 (wheelbase 350 mm, 1.28kg total weight, including batteries; Figure S2, supplementary
156 material). Its hovering time was about 23 min.

157 The current Civil Aviation Safety Australia (CASA) regulations restrict the use of small (< 20
158 kg) unmanned aerial systems (UAS) to visual line-of-sight daylight operation, with a maximum
159 altitude of 400 ft which is approximately 120 m, and within a radius of 3 nmi outside of an
160 airport. Small UAS cannot be operated above any person or closer than 30 m of populated areas,
161 houses and people, and are not permitted for research unless the research institution has been
162 granted a permit. This is possible if the institution has an experienced UAV pilot who is a radio
163 controller specialist, has a license for commercial UAV operation, along with appropriate
164 liability insurance . The Queensland University of Technology (QUT) fulfils this requirement
165 through its Australian Research Centre for Aerospace Aviation (ARCAA), with two pilots who
166 are in possession of commercial UAV licenses.

167 The DJI S800 was chosen for this study because it is designed to operate under the 20 kg AUW
168 class of UAS and so reduces operation costs, and avoids being subjected to the tighter
169 regulations for larger platforms.

170

171 **2.3. Instrumentation**
172 **2.3.1.PNC**

173 This study used the Mini Diffusion Size Classifier (DISCmini), developed by the University of
174 Applied Sciences, Windisch, Switzerland (Fierz et al. 2008). The DISCmini is a portable,
175 battery-operated monitor which can be used to measure number concentration of particles in the
176 size range 10-500 nm at a fast time resolution of 1 s (1 Hz). The instrument can measure PNC in
177 a range from $5 \cdot 10^2$ to over 10^6 p/cm^3. The instrument operates by electrostatically charging the

aerosols using a corona discharge and measuring their total surface charge. The accuracy of the measurement depends on the particle size distribution and is within ± 10-15%, as determined against a reference condensation particle counter (CPC). The advantages of using the DISCmini are its relatively small dimensions (180 x 90 x 40 mm), light weight (640 g, 780 g with the probe used) and long battery life (up to 8 hrs). Importantly, it can easily be integrated on the UAV. However, careful positioning of the DISCmini is essential in order to avoid possible issues with the stability of the UAV.

2.3.2.Meteorological data

An automatic portable Monitor weather station (Automatic Weather Station, Monitor Sensors (Aust) Pty Ltd.) was used to measure and log the air temperature, relative humidity, atmospheric pressure, solar radiation intensity, wind speed and wind direction in real time at intervals of 5 s.

2.4. Study design

The measurements were conducted over the three days of 19 February, 30 March and 8 April 2016 (day 1, 2 and 3) all of which were weekdays. Days 1 and 2 were used to optimize the study design, so different vertical flight paths were tested starting from 20 to 60 m and then from 5 to 60 m. The vertical flightpath design was optimized in order to ensure the safety of flights close to the ground, and to measure PNC distribution along the selected atmospheric column. On day 3, the flight path was increased to 100 m still in accordance to the maximum height restriction of 120 m permitted by the Civil Aviation Authority. The optimized design path of 5 to 100 m was adopted on that day 3, and sampling time was limited to the period of 10 am to 4 pm in order to avoid the morning and afternoon rush hour traffic, and thus to have a steady and consistent traffic flow rate.

Since the closest permitted approach to the Motorway was 30 m, and the minimum altitude 5 m, the measurements were conducted adjacent to the Motorway in an area that was relatively free of trees, as indicated by point A, Figure 1 and Figure S3. This location is where the UAV was operated in a vertical path, climbing to 60 m or 100 m altitude depending on the pre-programmed flight plan. Point H in Figure 1 represents the 'home point', which in UAV terminology refers to where it takes off and lands. The base camp, B refers to where the UAV operators and scientists were stationed. Point C represents the position of the automatic portable Monitor weather station.

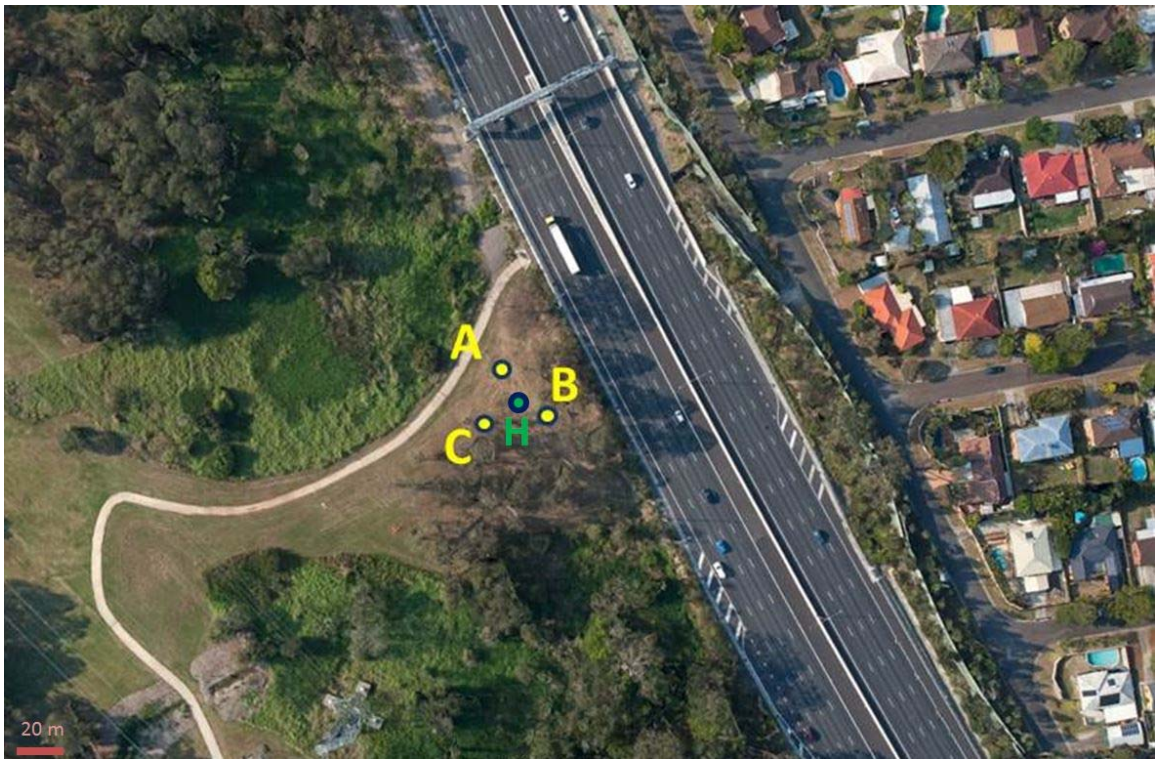

Figure 1: Google Earth Image with locations indicated as follows: A - the UAV vertical flight starting point, B - the base camp, C - the Monitor weather station, H – "home point" of the UAV.

2.5. Experimental procedure

The UAV can fly either manually or autonomously, and as a safety precaution the manual flight mode was selected for every take-off and landing. Once in the air, the UAV was switched to

autonomous flight mode, allowing the platform to follow the pre-programmed flight path of waypoints.

The DISCmini was fitted onboard, underneath the UAV at the beginning of each measuring day (S1 Figure), and with such payload it could fly for about 12-15 min before landing at the home point (point H, Figure 1).

A typical flight path consisted of a vertical ascent and descent of the atmospheric column, starting at an altitude of 5 m (above the ground point A, Figure 1) and climbing to 60 m at a steady speed of 1.5 m s^{-1} during days 1 and 2 or up to 100 m at a steady speed of 2 m s^{-1}on day 3 Both speeds allowed a significantly continuous number of flights (ascents and descents) before the battery was exhausted. With each battery, a maximum of 9 ascents and 9 descents were obtained for the 5 to 100 m flightpath, while a maximum of 14 ascents and 14 descents were achieved for the shorter flight path from 5 to 60 m. Figure 2 shows a screenshot of the ground station software, taken from the laptop computer used in field, during a typical 5 to100 m flight path. The programmed flights were observed before, during and after its execution. The two programmed waypoints at 5 and 100 m are also shown together with real time altitude and speed. Finally, the total flight time and the total estimated time of an ascent plus a descent are shown on the screen. PNC measurements were taken on the upwind side of the motorway at ground level just before and after the programmed flights on the downwind side.

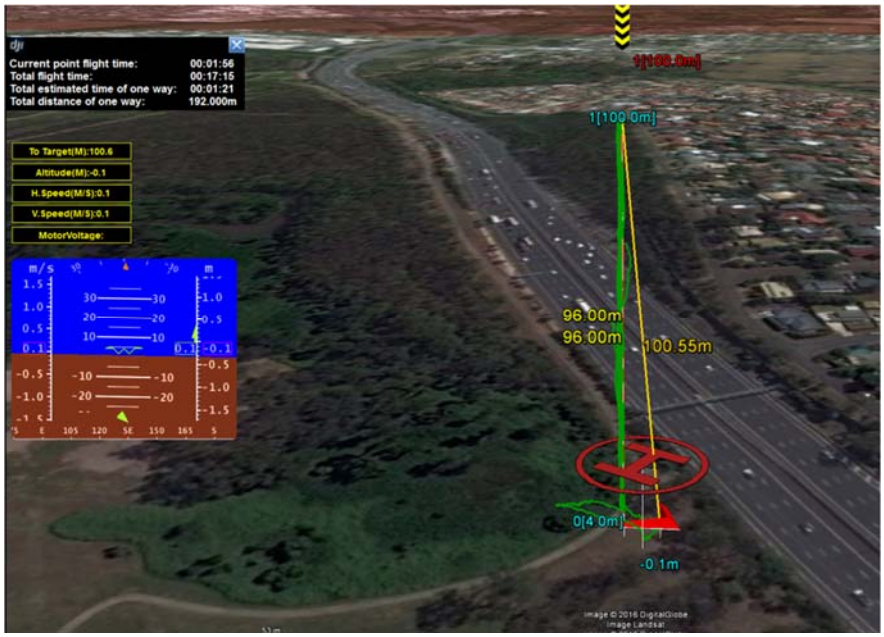

Figure 2. Screenshot of a typical flight path – a vertical flight from 5 to 100 m

The traffic flow rate during the hexacopter UAV vertical flights was determined by the video footage captured by the camera mounted on the Phantom quadcopter. This UAV was operated manually by the second ARCAA pilot. It was set to hover at a height of about 60 m above a point on the ground that was about 40 m away from the kerb of the motorway.

At the beginning of each day, all devices, including the weather station, were fully charged, switched on and were synchronized to the same time with a precision of ± 1s. Devices were switched off only at the completion of all measurements. The onboard devices, DISCmini and AARONIA data logger were activated to log data simultaneously from take-off to landing. The logging of data on both devices was terminated at the same time after each flight and data were downloaded to the computer.

3. Results

The UAV system, with the onboard DISCmini, measured the vertical distribution of PNC, acquiring data from 34 ascents and 34 descents from near the ground up to an altitude of 60 m

248 during days 1 and 2. Data from 9 ascents and 9 descents from 5 to 100 m were acquired on the
249 third day using the optimized flight path. There were the data used for the analysis.
250
251 **3.1. Meteorological conditions**
252 Wind conditions, followed two main patterns for most of the time. The wind speed ranged from
253 3 - 7 m s^{-1}. The wind direction was predominantly from the NE or E which corresponded to a
254 direction from the Motorway towards the adjacent tree-free area where the measurements were
255 conducted (from the Motorway to point A in Figure 1). Occasionally wind gusts were
256 experienced during the measurements and they were identified and later considered in the
257 analysis by the automatic weather station and those from the GPS datalogger.
258 The wind rose graph in Figure 3, illustrates the wind data recorded with the automated weather
259 station, for the duration of all the 5 to 100 m vertical flights, on day 3. In the case presented, the
260 prevalent wind direction was from the E and ENE.
261 The wind direction changed occasionally to W and WSW in the opposite direction and when this
262 happened the pollutants from the motor vehicles were not received at the measurement site and
263 therefore the data were not usable for our purpose. The shaded section in Figure 3 represents
264 wind directions which were not suitable for the measurements. As a result, 2 of the 9 complete
265 flights (ascents and descents) of the 5 to 100 m vertical flight were excluded from the analysis.

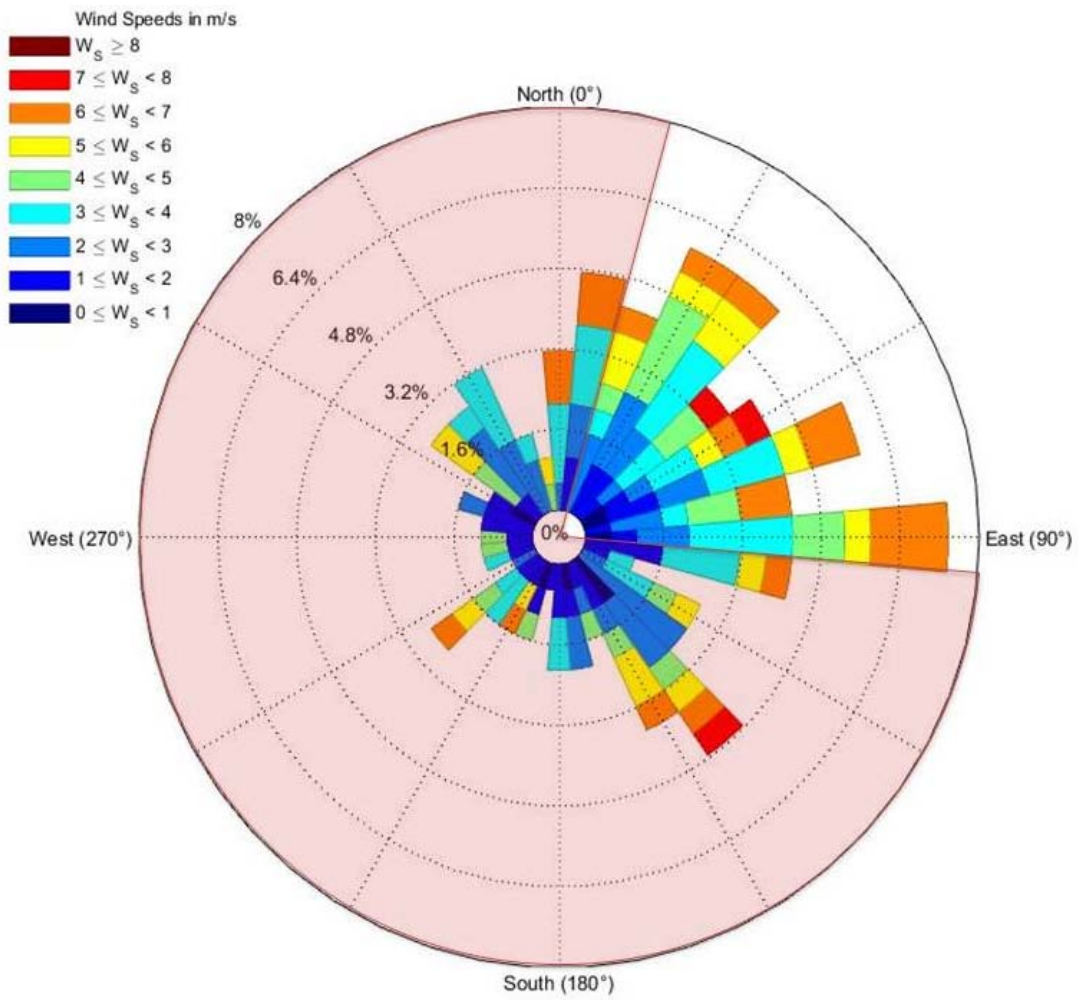

Figure 3 – Wind rose showing wind speed and direction, during the time period of the 5 to 100 m vertical flights.

3.2. Traffic conditions

The traffic flow rate during all three days of measurement in the four lanes of the motorway was in the range of 110-130 vehicles min^{-1}, of which about 20% were heavy-duty diesel vehicles. Most traffic moved freely at a steady speed of about 100 km h^{-1}.

3.3. Ascent and descent measurements

Figure 4 (a) and (b) shows the PNC distributions together with the traffic flow rate, of a typical 5 to 100 m ascent and descent. The graphs in Figure 4 show that the PNC varied by an order of magnitude over the entire profile, with the greatest variation being observed closest to the ground. The flight presented in Figure 4 (b) shows that the PNC increased up to 10 m from the ground before PNC starts to decrease sharply with altitude, within the first 20 m, and then decreasing gently. PNC did not vary significantly at heights above 35 m. This unexpected pattern, of the PNC increasing up to 10 m, was observed in some ascents and descents. This phenomenon will be further discussed in the Discussion.

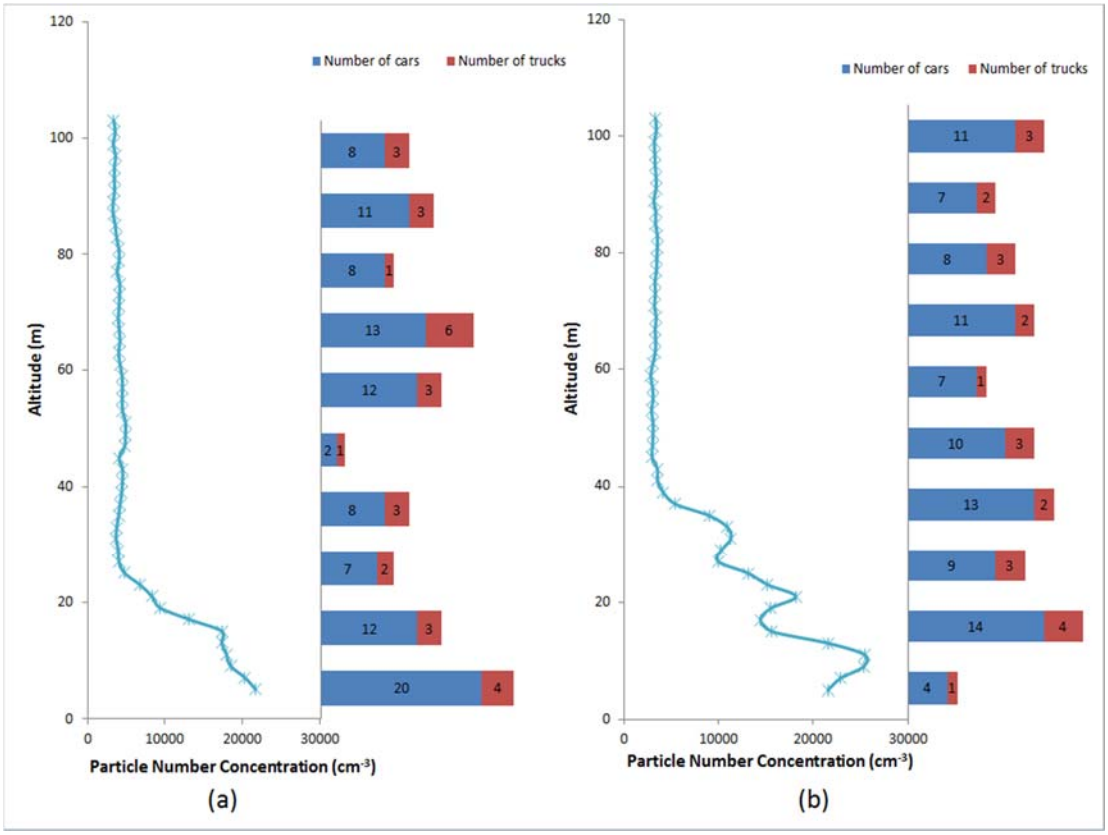

Figure 4. Typical PNC profiles (left) and corresponding histogram of the traffic flow rate presented in 5s intervals (right) of an ascent (a) and a descent (b) between 5 and 100 m.

The PNC profiles in the ascents and descents were expected to be similar. To verify, the mean PNC was plotted at a given altitude during the ascents against the mean PNC during the descents

as shown in Figure 5. At a given altitude there was a good correlation between the PNC measured during both the ascents and the descents.

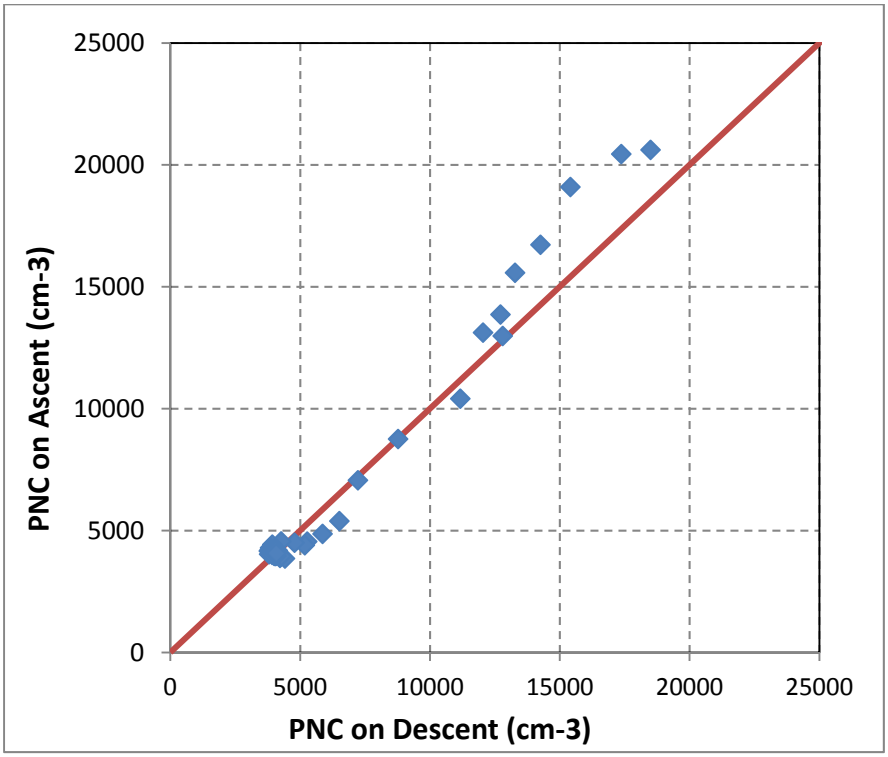

Figure 5. Mean PNC of the ascents (Y axe) and descents (X axe) for the flights between 5 and 100 m.

Figure S4 (supplementary material) shows the mean, with standard deviations of the PNC measured during (a) the seven ascents and (b) seven descents of the 5 to 100 m vertical flights.

Figure 6 shows the mean with standard deviations of all 14 PNC vertical profiles of the 5 to 100 m flight path, consisting of 7 ascents and 7 descents, combined together. The mean PNC decreased sharply from 5 m to 15 m, and then decreased very gently up to 18 m. The mean PNC then decreased sharply again, and attained the steady value of $4 \cdot 10^3$ p/cm^3 at about 40 m. The mean PNC dropped by an order of magnitude in a height of less than 20 m.

Figure S5 (SI) shows the mean with standard deviations of all 24 PNC vertical profiles of the 5 to 60 m flight paths acquired during days 1 and 2. While these data were not used for the

analysis, as they are acquired to optimize the procedure, it can be seen that the trends in the vertical profile are the same on day 3.

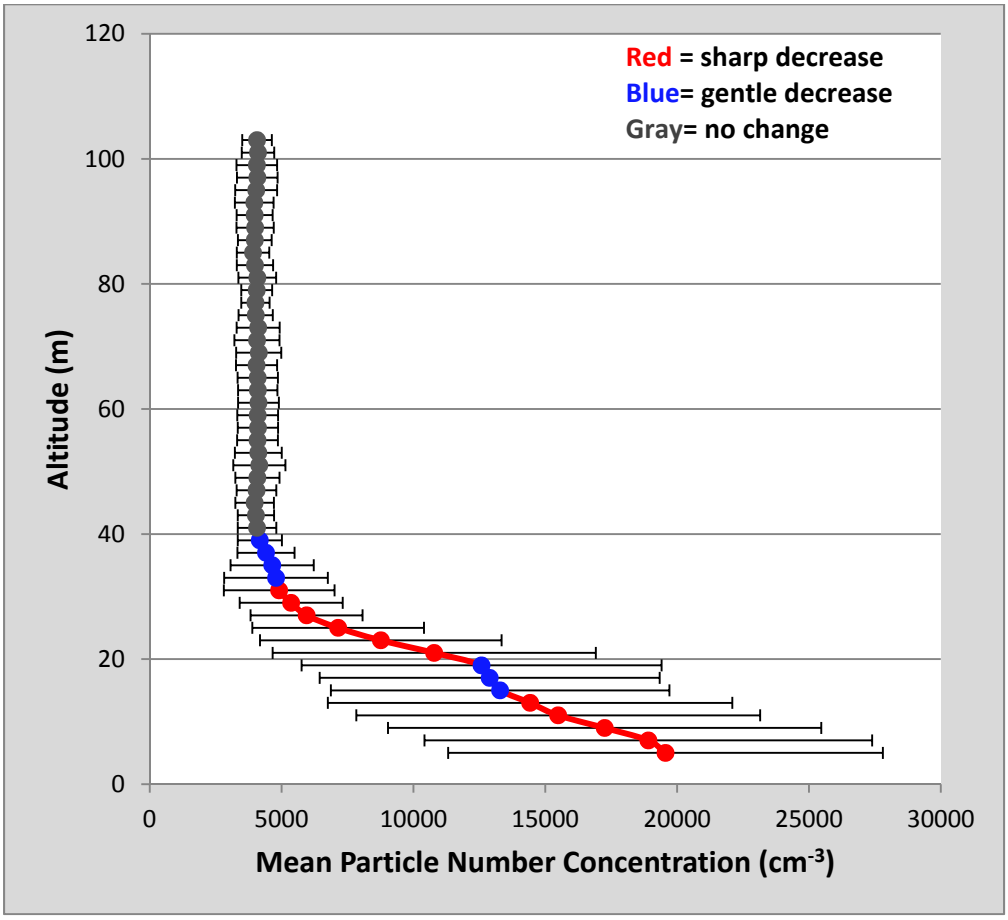

Figure 6. PNC mean with standard deviation of both seven ascents and seven descents during the 5 to 100 m vertical flights.

4. Discussion

This study assessed the vertical distribution of traffic generated pollutants in an open space adjacent to a motorway. This was achieved by customizing and flying a hexacopter UAV vertically through an atmospheric column (0-100 m). The choice of the DJI Wookong autopilot was based on the technical features of the UAV platform. Such autopilot was the most reliable to be used with the S800 hexacopter because both autopilot and UAV are produced by DJI. Future work will include a focus on other UAV autopilots (Pixhawk) to be integrated with the S800.

Different autopilots have serial and analog input connections for further sensor integrations with the possibility of temperature profile and other atmospheric parameters measured in flight. We demonstrated the feasibility of a new system, which measures with high spatial and temporal resolution (time: 1 s; space: ± 0.5 m) the variation of traffic generated PNC as function of height in an open space adjacent to a busy motorway, as presented in Figure 7a.

The use of this UAV system allowed for the first time, to the knowledge of the authors, to determine the vertical distribution of PNC, from 5 up to 100 m, continuously. Our study, established that the PNC in the atmospheric column decreased sharply from 5 m, up to about 15 m before starting to decrease very gently up to 18 m. Then, the PNC decreased sharply again reaching a steady value after 40 m. The PNC was measured at ground level at the upwind side of the motorway before and after the downwind measurements and showed readings in the range of 600 – 1000 p/cm^3. The corresponding ground level PNC readings on the downwind side of motorway were in the range of 35,000 – 45,000 p/cm^3, indicating that the large majority of pollutants originated from motor vehicles travelling on the motorway.

This study showed that the traffic generated PNC above the ground (5 m), during the period to 10 am to 4 pm, outside the rush hours, were of the order of $2 \cdot 10^4$ p/cm^3, and it attained a steady value of the order of $4 \cdot 10^3$ p/cm^3 above a height of 40 m. Therefore our results suggest that emissions from vehicles on the motorway did not directly affect the environment above this height. Using this hexacopter UAV system to assess the PNC vertical profile throughout an atmospheric column, in open spaces adjacent to a traffic motorway, provided knowledge to improve dispersion models to better protect populations living close to such pollutant sources. Such measurements were previously not possible with fixed-site measurements at ground level, or from a distant tall building, and this is a significant finding.

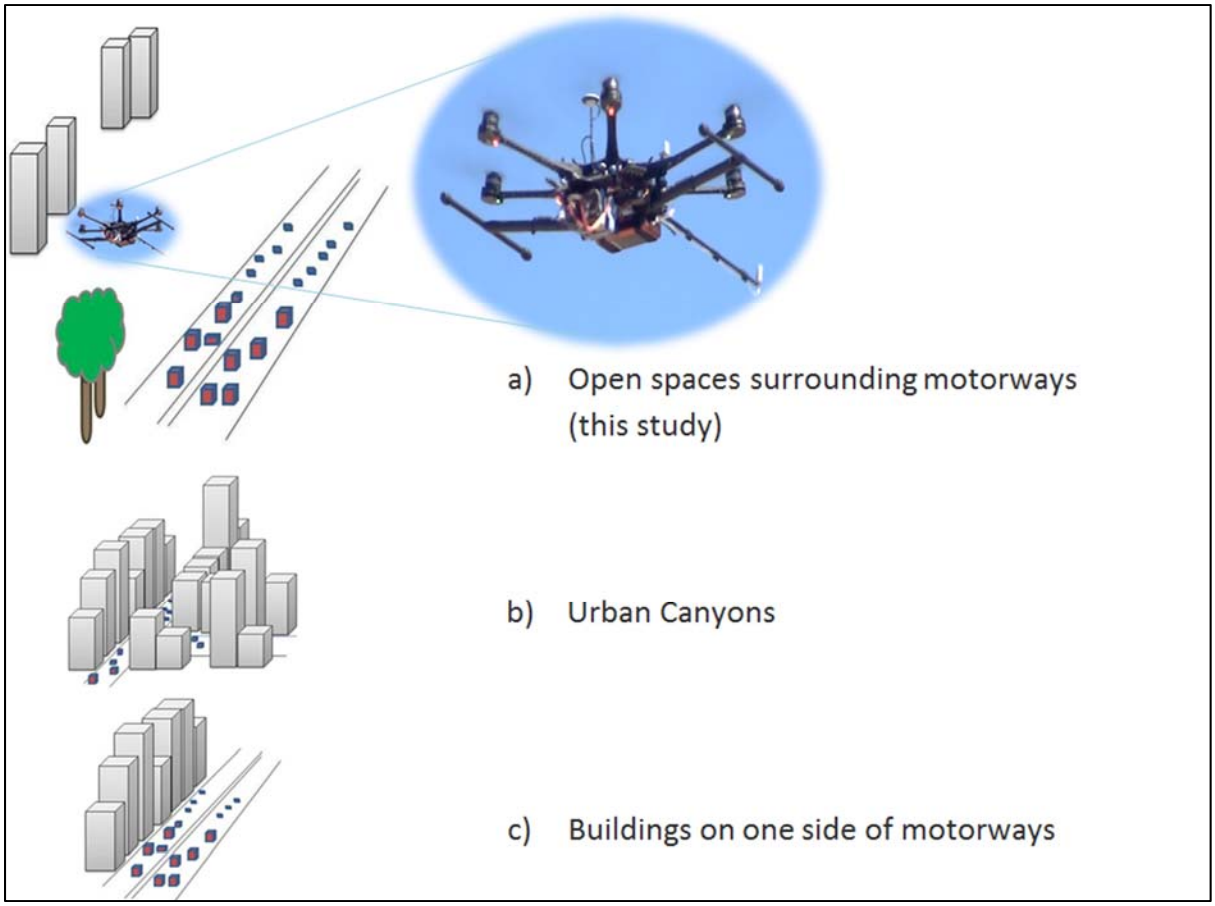

Figure 7. Schematic representation of urban environments

This study in an open space environment adjacent to a motorway differs from other studies conducted in constrained urban environments, such as in urban canyons (Figure 7 b), which are typically relatively narrow streets with buildings lined up continuously along both sides (Nicholson 1975). Figure 7c presents a different scenario from narrow urban canyons, one where buildings are lined along only one side of a major road. Here, the air travels a sufficient distance downwind of the first building before encountering the next (Vardoulakis et al. 2003). The vertical particle mass concentration profile in such cases largely shows a consistent decrease in concentration with increasing distance from nearby streets (Chan and Kwok 2000; Micallef and Colls 1998; Rubino et al. 1998).

In general, all these previous studies have illustrated that both PNC and PM decreased with altitude next to high rise buildings in street canyons (Vardoulakis et al. 2003). An important observation made in the present study, which differs from previous ones of both urban canyons and buildings near traffic roads, is that in some cases the PNC in the vertical plane increases from the ground up to about 10 m before starting to decrease with height. We attribute this to the fact that the exhaust tubes of most heavy duty trucks project vertically upwards and are located at a height of some several meters above ground. A significant proportion of vehicles on the traffic motorway, from 20 to 30 % of the total traffic count, consisted of heavy-duty diesel trucks. This is not the case in urban canyons where most of the vehicles were motor cars with the tailpipes close to street level. Another observation we made, is that the mean PNC values during both the ascents and descents had very similar patterns as shown in Figure 5. The average PNC for ascents at a given altitude did not differ significantly to the average PNC at the same point during the descents. This was the first application, to the knowledge of the authors, of UAV for the determination of PNC vertical profile of urban air quality; previously UAV systems have been used to investigate aerosol vertical profiles at the ocean coast (Brady et al. 2016).

5. Conclusion

In this study we have presented the potential for broader applications of UAV systems in assessments of the PNC vertical profile. However, it is the strict civil aviation regulation for UAV deployment that currently limits the use of UAV systems for PNC measurements, specifically in urban environments.

Moreover, this hexacopter UAV system can be utilized in environments where UAV use is less strict, such as open spaces away from urban centers or to monitor concentrations and dispersion of plumes emitted by industrial stacks and ships in the ocean.

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Appendix A. Supplementary material

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Supplementary Material (SM) For:

Determination of the Vertical Profile of Particle Number Concentration Adjacent to a Traffic Motorway using an Unmanned Aerial Vehicle

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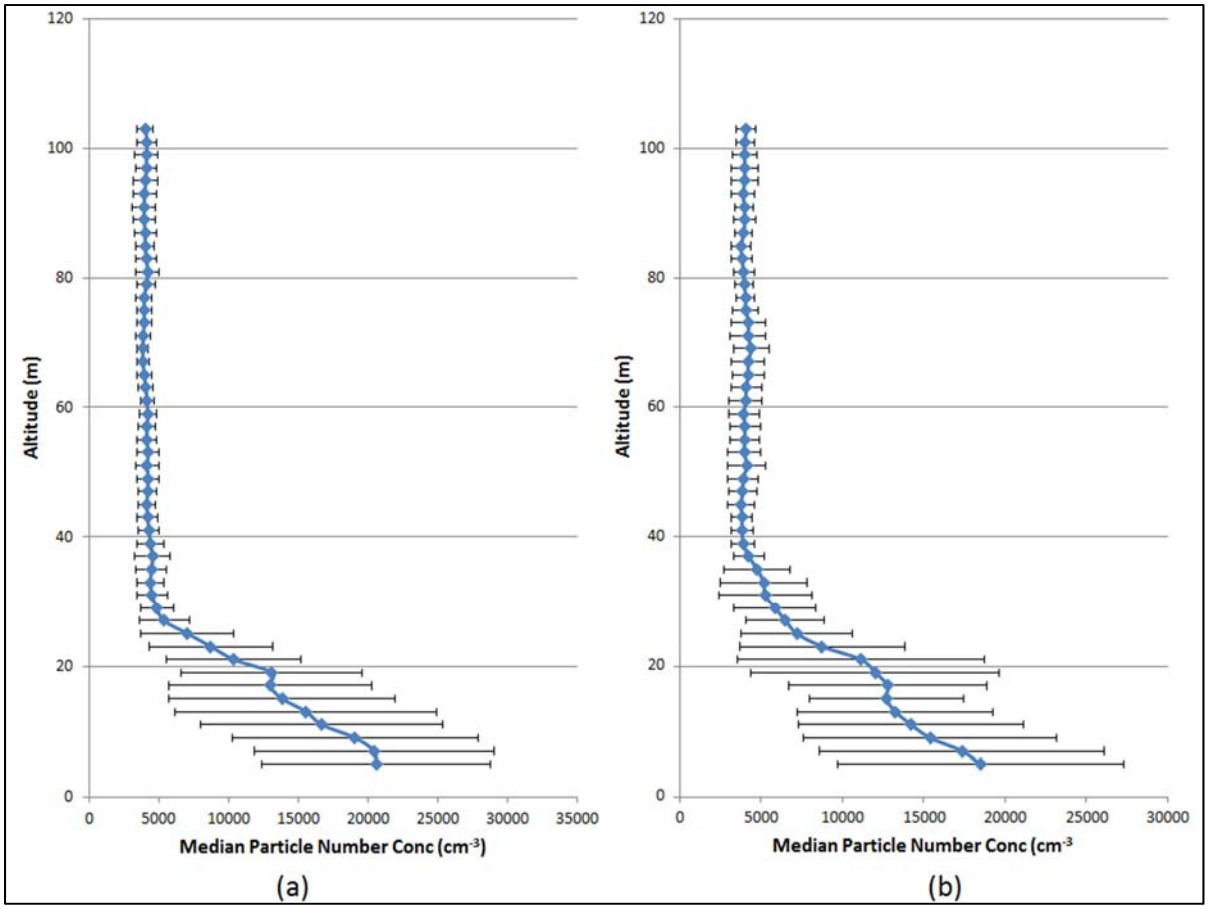
Figures 5

Figure S1: The UAV system. the DJI S800 UAV with the DISCmini mounted onboard.

Figure S2: S800 hexacopter and the Phantom quadcopter

Figure S3: Aerial photo of the base camp and station



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491 **Figure S4:** Means and standard deviations of the seven ascents (a) and descents (b) of the flights
492 between 5 and 100 m.

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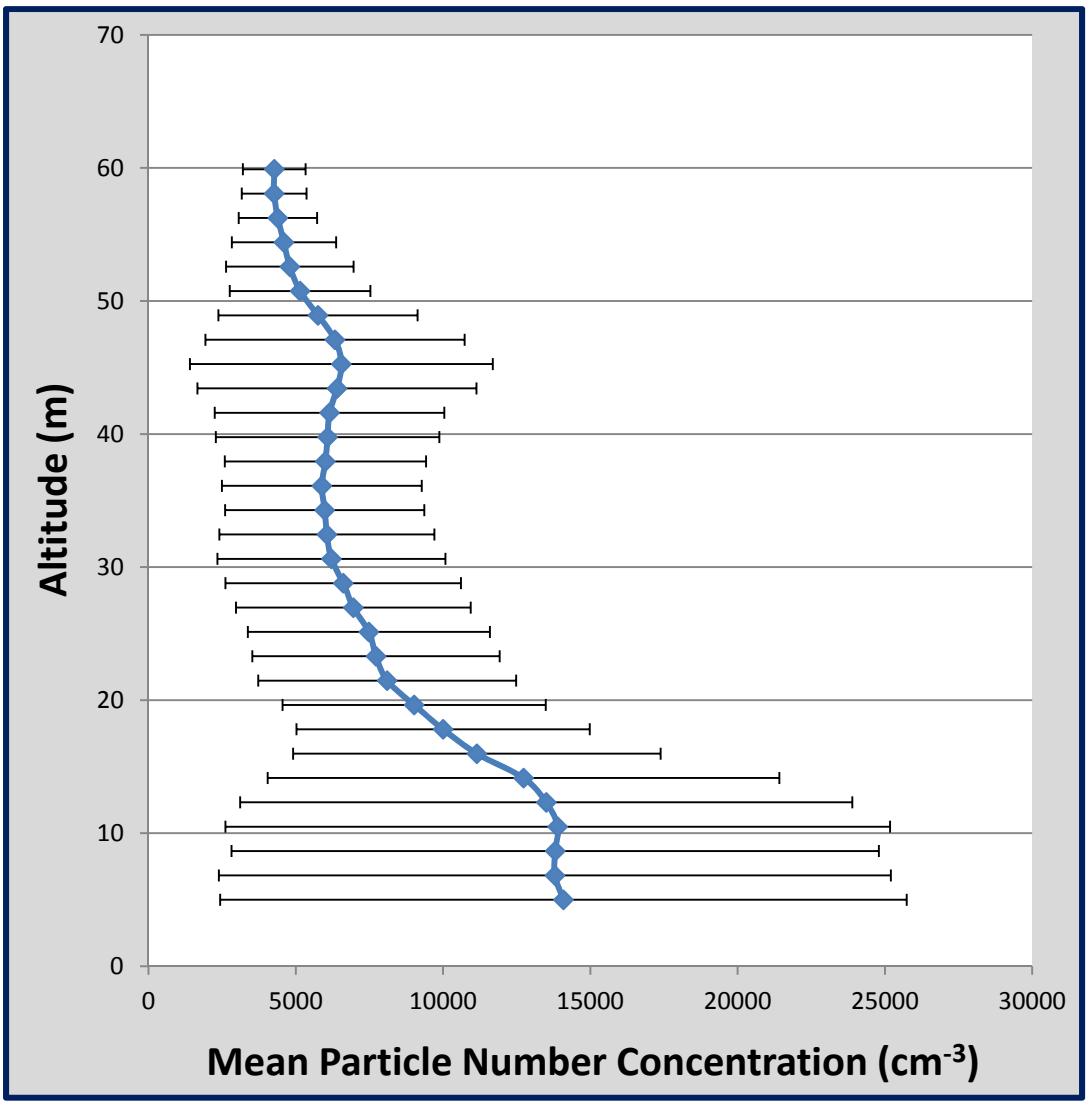

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495 **Figure S5:** PNC mean with standard deviation of both 12 ascends and 12 descents during the 5
496 to 60 m vertical flights acquired during the optimization of the flight design.

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