Profiling the Lower Troposphere Using the Research UAV 'M^{2}AV T200 Carolo'

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Figure 1. The autonomous research aircraft M^{2}AV *after landing during a field experiment on Majorca, 2007. The white dome at the nose contains the meteorological sensors. The position lights e.g. at the wing tips allow for operation at night.*

ABSTRACT

Vertical profiles using an automatically operating small research UAV (unmanned aerial vehicle) named M^{2}AV were performed at Halley station in Antarctica and over heterogeneous land surface near the Meteorological Observatory Lindenberg (MOL). Both mean and instantaneous vertical profiles are shown. All profiles show good agreement with other *in situ* measurements (towers) and remote sensing data (sodar, wind profiler with RASS). During the LITFASS-2009 field campaign in July, 2009, vertical profiles up to 1500 m agl were performed automatically using an M^{2}AV for the first time. The data sets are not analysed yet, this article gives a very first sight into the measurements. The M^{2}AV data show fine details of the turbulent structure of the lower troposphere due to a vertical resolution of a few centimetres. However, the recently obtained data sets are subject to detailed error analysis in the future.

1. INTRODUCTION

The *in situ* measurement of vertical profiles is important to characterise the fine vertical structure of the atmospheric boundary layer (ABL). For instance, the dependence of the potential temperature on altitude defines the thermal stratification. The mechanical shear (i.e. the variation of wind speed and direction) produces turbulence and thus turbulent fluxes. The top of the ABL is required for scaling approaches (e.g. Deardorff scaling in the convective boundary layer, local scaling in the stable boundary layer).

Vertical profiles up to large altitudes can be obtained by remote sensing. Generally, these strategies are indirect and rely on many physical assumptions. Also both spatial resolution and accuracy are not comparable to *in situ* measurements. Towers are not mobile and too short. Tethered balloons at large altitudes are complicated to use. Radiosondes are easy to use and not very expensive but offer poor spatial and temporal resolution.

The spatial resolution of a research aircraft is significantly higher. Especially the wind measurement is very accurate when using an aircraft that is equipped with a proper flow sensor (a five-hole probe, 5HP) and an attitude measurement system (e.g. a combination of GPS and an inertia measurement unit). During flight it is important to maintain flow angles (side slip and angle of attack) within the calibration range (typically 10 to 20 degree). This limits the vertical speed (the rate of climb and descent) of the research aircraft. An important drawback of manned research aircraft are the acquisition and running costs. For this reason and for measurements sites where manned aircraft can not be operated, the use of small, unmanned and automatically operating research aircraft (Fig. 1) is very attractive.

In general there are two approaches to measure vertical profiles with research aircraft. Instantaneous profiles (slant flight pattern) are suitable if only little time is available, if the ABL is very in-stationary (or the aircraft is slow), if the dependence of the profile on time is requested (repeated slant flight patterns over one location) or if the dependence of the profile on the location is requested (saw-tooth pattern). It is very important to use fast sensors. If the sensor response time is too large, the vertical profiles have large systematic errors when the aircraft is climbing or descending rapidly. In the following, this approach is demonstrated by recently measured LITFASS-2009 data, below.

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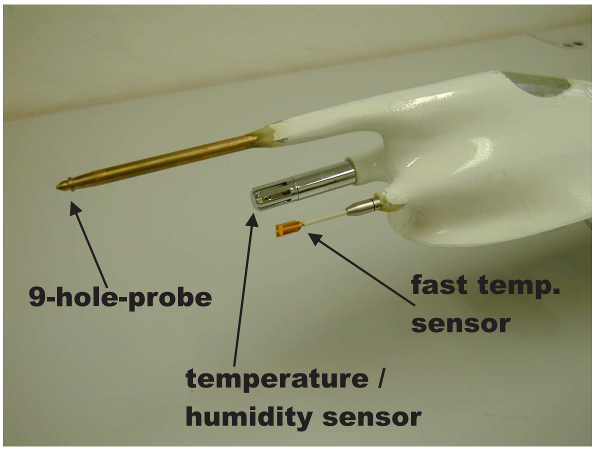

Figure 2. The sensor dome of the M^{2}AV.

For mean profiles, several horizontal straight and level flights (legs) at several altitudes within the ABL have to be performed. This is only suitable if the research aircraft is very fast and is equipped with extraordinarily fast sensors. Also the ABL has to be stationary and horizontally homogeneous. This strategy was chosen during an Antarctic campaign, the results are shown below.

2. INSTRUMENTATION

The Meteorological Mini Aerial Vehicles (M^{2}AV, Fig. 1) are self-constructed, automatically operating research aircraft (Spieß *et al.*, 2007; van den Kroonenberg *et al.*, 2008) of 6 kg in weight (including 1.5 kg scientific payload) and 2 m wingspan. These systems are capable of performing turbulence measurements (3D wind vector, temperature and humidity) and can be applied for measuring vertical profiles of the lower troposphere. A M^{2}AV is hand- or bungee-launched which makes handling and operation easy. With an endurance of approximately 50 minutes, the range accounts for 60 km at a cruising speed of 22 m s^{-1}. For the mounting of the meteorological sensors a sensor dome at the nose of the aircraft (Fig. 2) was constructed to minimise the aircraft's influence on the measurements and to get the sensors positioned close to each other.

The autopilot hardware of M^{2}AV Carolo T200 consists of several modules. For flight guidance and control, a mini computer called 'TrIMU' is implemented (Buschmann *et al.*, 2004; Winkler and Vörsmann, 2007) which includes three IMU (inertia measurement units) and controls the aircraft servos. The aircraft operates automatically i.e. without a remote control. Way-points and altitude are defined by the user via a ground station (laptop computer) before take-off but can be changed during flight as long as the M^{2}AV is within 5 km range. All meteorological sensors are connected by a synchronous serial interface to a second TrIMU which is used for the data acquisition of the meteorological sensor package. The data are stored in binary format on a standard multimedia flash card (MMC). The total power consumption of the meteorological data acquisition system is less than 1 W.

Since a main application of the M^{2}AV is the investigation of turbulent fluxes in the ABL, the M^{2}AV was equipped with fast sensors and data acquisition at 100 Hz. The flow at the nose of the aircraft and the static pressure are measured by a miniature 5HP that has a mass of 22 g and a diameter of 6 mm. It was designed for the measurement of angles of attack α and side slip $\tilde{\beta}$ in the range of -20^o to $+20^o$, respectively. For the calculation of the meteorological wind vector the attitude and the ground speed of the aircraft is required with high precision. The navigation computer of the M^{2}AV provides navigation data which are stored on a second MMC. All three ground-speed components as well as the pitch and roll angles are calculated based on a single antenna GPS system in combination with IMU.

Air moisture and temperature are measured using a Vaisala Intercap sensor (Fig. 2) that fulfils the requirements regarding size and mass. Unfortunately, the sensor is characterised by large response times during large humidity and temperature changes. However, under normal flight conditions in the ABL its spectra reproduce the inertial sub-range of turbulence up to 1 or 2 Hz, and its absolute accuracy is about ± 0.6 K air temperature and ± 2% relative humidity, respectively, over a wide temperature range. Fast temperature fluctuations are measured by a thin thermocouple with a fragile mechanical design and rather poor long-term stability but a short response time in the range of 1×10^{-2} s. By complementary filtering, the signals of the two temperature sensors are combined, resulting in long-term stability with high accuracy and resolution in an ambient-temperature range of -40^oC to $+60^o$C.

3. SHORT PROFILES IN ANTARCTICA

In 2006 British Antarctic Survey (BAS) started a cooperation with the Institute of Aerospace Systems (ILR). In total three M^{2}AV operated from October, 2006, until December, 2007, at BAS Halley station. This was the first time that unmanned research aircraft were used in Antarctica. At a minimum surface temperature of -20^o 16 flights around the station and four flights across the ice edge were performed. One focus the measurement of vertical profiles of temperature and wind above the 32 m tower at Halley. A further comparison with a remotely sensing system was not possible due to a lack of sodar data. Fig 3 shows mean vertical profiles of wind speed and direction as well as air temperature during two flights under quite stationary conditions. The data of both flights agree well. A linear dependence on height was found for all three quantities in good agreement with the tower data.

4. LONG PROFILES NEAR LINDENBERG

For a direct comparison of airborne measured profiles at larger altitudes (up to 1000 m and above) M^{2}AV were operated several times at the Meteorological Observatory Lindenberg (MOL) in cooperation with the German Meteorological Service DWD (e.g. Beyrich *et al.*, 2002).

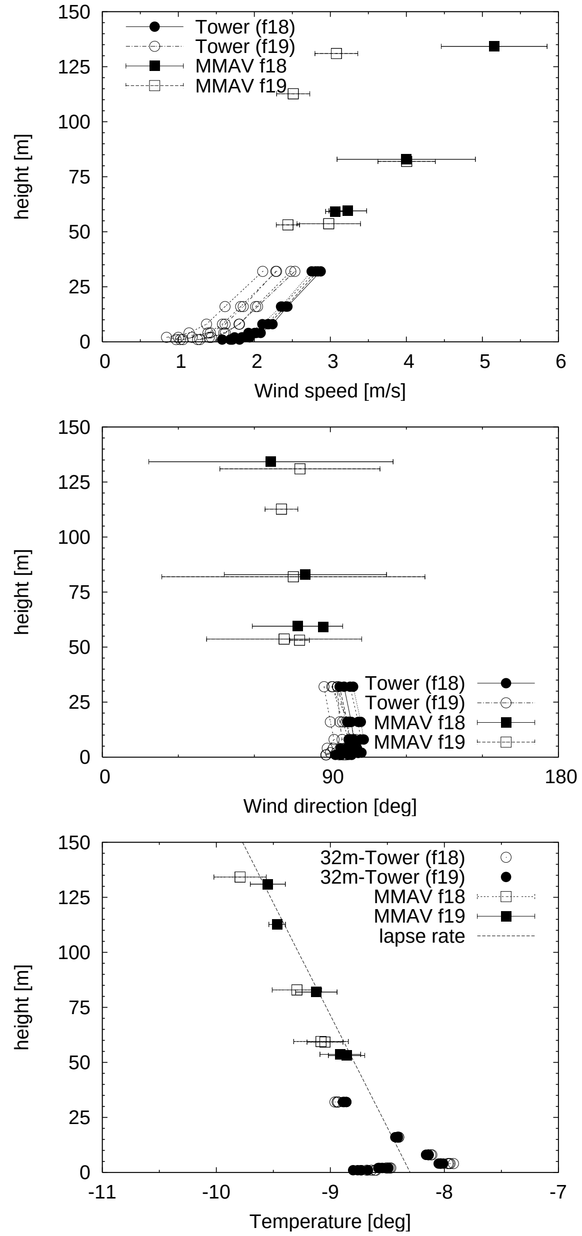

Figure 3. Example of vertical profiles measured at Halley station, Antarctica.

At the MOL, a 99 m tower, a sodar and a wind profiler with RASS provide continuous vertical profiles of virtual temperature, wind speed and direction. In July, 2009, in the framework of the LITFASS-2009 field campaign, vertical profiles using the M^{2}AV were performed automatically with maximum heights above 1000 m agl, for the first time. Due to a lack of experience with the behaviour of the autopilot at large altitudes, firstly a sub-optimal flight plan was commanded. The vertical profiles in LITFASS-2009 consisted of 'piled' squares with straight flight sections of about 700 m length. This flight pattern was chosen to meet the requirements of the German aviation authorities that demanded to keep the M^{2}AV always within sight during the vertical profiles. There are two main drawbacks with this flight pattern: 1) It contains many turns during those the roll and pitch angles of the aircraft left the calibration range of the 5HP. 2) It contains larger sections of horizontal flight since the possible climb rate of the M^{2}AV was under-estimated. In future missions this problem will be solved by improved flight planning, of course. But for the present flight, sections with roll angles outside 0 ± 5^o and fast changes in pitch were cut out of the data.

Fig. 4 shows vertical profiles of wind speed, direction and temperature during a flight on 21 July, 2009, starting at 7 UTC. The vertical profile took 22 minutes (ascent and descent; Fig. 4 shows only the ascent). Local time was plus two hours, thus no fully developed convective ABL could be expected. The cloud cover during the flight was about 2/8 *alto cumulus*. For comparison, the figures show also tower, sodar and wind profiler data, averaged over several minutes. Especially the temperature and wind direction (above 100 m) measured by sodar, wind profiler and M^{2}AV agree very well. The wind speed measured by M^{2}AV, tower and sodar also agree well, while the wind profiler shows much less variations with height compared to the M^{2}AV.

All three parameters depict a strongly turbulent layer below 300 m agl, indicating a shallow convective ABL. Airborne measured wind direction and speed still show many variations with height above 300 m. In further data analysis the effect of a possibly non-perfect wind-vector calibration has to be examined. Also it has to be inspected whether the variations in air temperature were due to changes in flight direction and thus due to an improper shielding of the temperature sensor against solar radiation.

5. CONCLUSION

Small research UAV are an attractive alternate to expensive manned aircraft. Worldwide, there are many systems under development, but only few can be operated automatically. As presented here, the M^{2}AV is able to perform vertical profiles up to 1500 m automatically and to deliver atmospheric data with high vertical and temporal resolution.

The diagrams shown from the LITFASS-2009 campaign are preliminary since the campaign was carried out only one month ago and data analysis has just begun. But even the preliminary comparison between M^{2}AV *in situ*

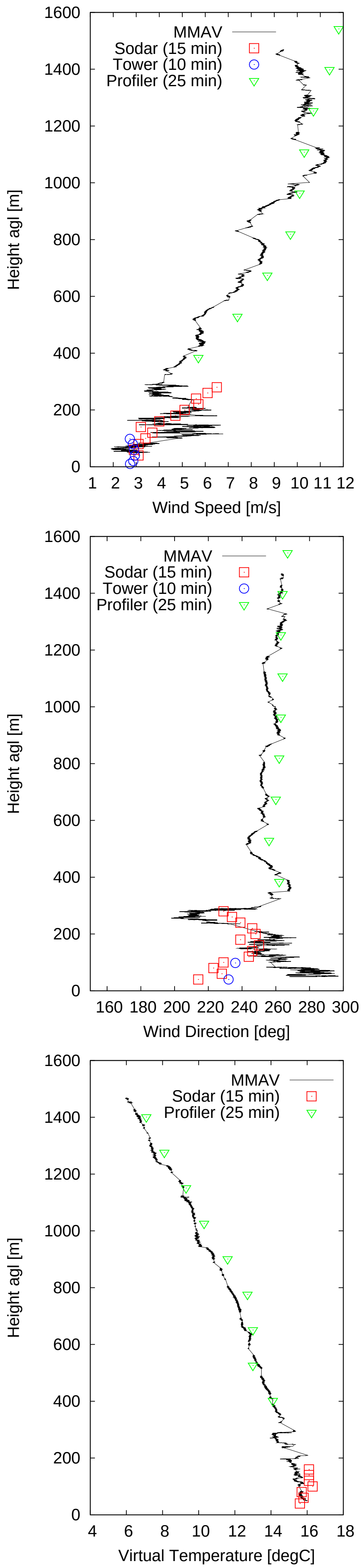

Figure 4. Vertical profiles measured in LITFASS-2009.

measurements and remote sensing data shows good agreement. It has to be noted that the sodar, wind profiler and tower data were averaged over several minutes (wind profiler data up to 25 minutes). The small systematic differences between wind profiler and M^{2}AV data can be explained by horizontal changes since the two systems operated about 5 km apart. Difference between tower and M^{2}AV data below 100 m are due to the heterogeneous surface of the experimental site. The lowest tower stations are mainly influenced by their direct surrounding, while the M^{2}AV covered a larger horizontal area.

The most evident difference between airborne *in situ* and remote sensing data is the vertical resolution. While the remote sensing systems delivered data with large vertical gaps, the M^{2}AV data show the turbulent fine structure of the ABL with a few centimetre vertical resolution (at 22 m s^{-1} airspeed, about 2.6 m s^{-1} climb rate and a sampling rate of 100 Hz).

However, with the experience gained during LITFASS-2009 it became clear that the vertical profiling of the lower troposphere using M^{2}AV can significantly be improved by 1) planning less turns i.e. using longer straight flight sections; 2) mounting a longer sun shield around the temperature sensor and applying black paint to the inside of the shielding tube; 3) planning a larger calibration square flight at constant altitude to improve the wind calibration as described by van den Kroonenberg *et al.* (2008).

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