7.4 COMPARISON OF M^2AV UNMANNED AIRBORNE METEOROLOGICAL MEASUREMENTS WITH REMOTE SENSING AND THE HELIPOD

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1. INTRODUCTION

Airborne meteorological measurements are essential within field experiments (e.g. Mahrt and Ek, 1993; Mahrt *et al.*, 2001). Since aircraft travel over a large distance in a comparatively short time, airborne measurements take a 'snapshot' of the atmospheric flow. Length scales between convection and small scale turbulence are covered. Thus airborne measurements are usually a good supplement to ground-based measurements and remote sensing (e.g. Beyrich *et al.*, 2002b). The airborne measurements are used for investigating the water and energy balance between the surface and the atmosphere as well as for parameterisation and validation of numerical models (e.g. Bange *et al.*, 2006; Beyrich *et al.*, 2002a). Furthermore, airborne data are compared with ground-based measurements and remote sensing for reference or cross-validation.

Today airborne meteorological research can be done with manned and unmanned aircraft. Within the last years more and more unmanned aerial vehicles (UAVs) were developed with different sizes and mass. Most of these UAVs were developed for military purposes. But in principle it is possible to use most of the aircraft also for civil purposes like meteorological measurements.

Both, manned and unmanned systems have advantages but also disadvantages. Generally spoken meteorological measurements with small unmanned aircraft (less than 10 kg in weight) have the disadvantage that the data quality is less compared to large research aircraft. Furthermore, the payload and thus the number of measurands is limited using UAVs. On the other hand especially the very small UAVs (micro aerial vehicle, MAV) are easier to operate. The operating and maintenence costs of MAVs are significantely less compared to a manned research aircraft.

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UAVs can operate were it is too dangerous for manned aircraft e.g., over volcano craters or at low level during the polar night. Since remote control is only possible within the range of sight, it stood to reason to develop a fully autonomous meteorological MAV (M^2AV).

The M^2AVs developed at the Institute of Aerospace Systems (ILR) at the TU Braunschweig are equipped with sensors to measure the temperature, humidity, static pressure and wind vector. Although the accuracy and resolution was expected to be less compared to a conventional research aircraft, the low operating cost are a clear advantage. Spatially distributed simultaneous measurements by a flock of M^2AVs become possible.

This paper will show results of analysed meteorological data sets measured by the M^2AV. In October 2005, the M^2AV participated the meteorological field experiment 'LAUNCH 2005' in Lindenberg near Berlin. The M^2AV data were compared with lidar and sodar measurements. Furthermore, an in-situ comparison of temperature, humidity and wind vector data with the helicopter-borne turbulence probe Helipod (Spieß *et al.*, 2004; Bange and Roth, 1999; Bange *et al.*, 2002) will give information about the M^2AV data quality.

2. MEASUREMENT SYSTEMS

Since the ILR has several years of experience in the field of airborne turbulence measurement with the Helipod, it stood to reason to use this knowledge to develop an autonomous M^2AV which is based on the 'Carolo' family.

The 'Carolo T200' is a self-constructed model plane with two engines and a wingspan of two metres - hence the name T200 (see figure 1). The maximum take-off weight is 4 kg, including 1500 g of payload. It is hand-launched which makes handling and operating the aircraft easy. With an endurance of approximately 50 minutes, the range accounts for 60 km at a minimum cruising speed of 20 m s^{-1}. For the mounting of the meteorological sensors a nose boom was constructed to minimise the aircraft's influence on the measurements and to get the sensors positioned close to each other (see Figure 2).

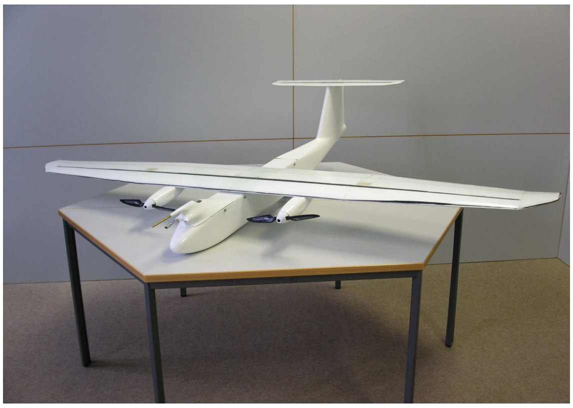

Fig. 1: *The autonomous research aircraft M^{2}AV based on 'Carolo T200'.*

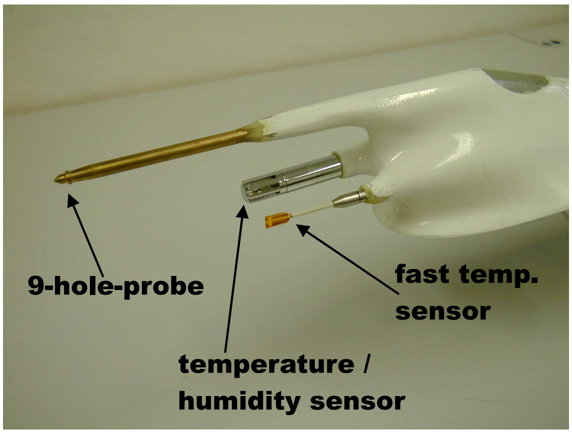

Fig. 2: *The noseboom of the M^{2}AV with the meteorological sensor package.*

Since one focus of meteorological research at the ILR is the investigation of turbulent fluxes in the boundary layer, the M^{2}AV was equipped with a miniature 9-hole probe. This probe was developed and manufactured by the Institute of Fluid Mechanics (ISM) of the Technical University Braunschweig. The 9-hole probe has a mass of 22 g and a diameter of 6 mm. It was designed for the measurement of angles of attack and sideslip in the range of -20^o to +20^o, respectively. For deriving the angle of attack and the sideslip, the relative pressures between the five holes at the tip of the probe is measured. Furthermore, the static pressure is measured via four holes at the side of the probe.
For temperature measurement, a split sensor concept seemed advisable: Two temperature sensors with different spectral characteristics are used. One sensor was made by Vaisala (Figure 3) with high absolute accuracy ($\pm$0.6 K) but slow response time in the magnitude of 1 s. The other sensor is a thin foil element with a more fragile mechanical design and rather poor long-term stability but fast response time in the range of 50 ms specially made by Dantec for the M^{2}AV (figure 4). By complementary filtering, the characteristics of both sensors are combined: Long-term stability with high accuracy and fast resolution of several milli Kelvin for a range of -40 ^{o}C to +60 ^{o}C.

Fig. 3: *The Vaisala HMP50 temperature and humidity sensor.*

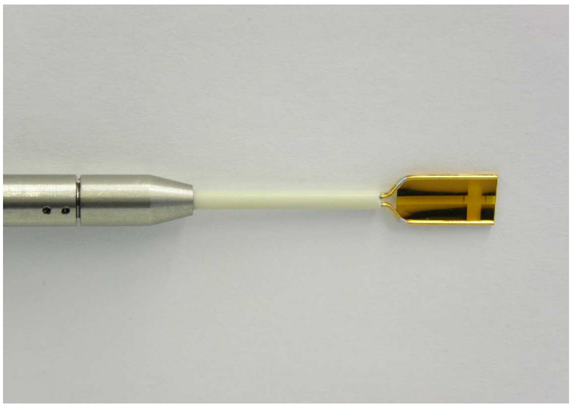

Fig. 4: *The fast foil sensor made by Dantec especially for the usage in the M^{2}AV.*

For measuring humidity, a Vaisala Intercap sensor (see Figure 3) was applied which fulfills the requirements regarding size and mass. The sensor is characterised by large response times (for large humidity changes). However,

its spectra reproduce the intertial subrange of turbulence until 1 or 2 Hz. The accuracy is about ±2% relative humidity over a wide temperature range.
For the calculation of the meteorological wind vector the attitude of the aircraft is needed in high precision. Although a multi antenna 3D-GPS system in combination with an accurate INS was most desireable it was not available until spring of the year 2006. However, the implemented autopilot provided some navigation data. Within the autopilot, all three ground speed components were calculated, mainly based on a single antenna GPS system. The pitch and roll angles were also determined and recorded.

3. DATA BASE

The M²AV had its first scientific mission during the 'International **L**indenberg campaign for **a**ssessment of h**u**midity **an**d **c**loud profiling systems and its impact on **h**igh-resolution modelling' (LAUNCH-2005) experiment. The M²AV was used to provide area-averaged mean values of humidity and temperature for comparison with the remote sensing systems which were located at the meteorological observatory Lindenberg (MOL) of the German meteorological service (DWD). A differential absorption lidar (DIAL) (Boesenberg and Linne, 2002) was located at Lindenberg, about 60 km south-east of Berlin. A sodar (Beyrich, 1997) was located at Falkenberg, about 5 km south of Lindenberg.
Between 12 October, 2005, and 14 October, 2005, four flights were carried out. On 12 and 13 October, 2005, the M²AV flights were performed at Falkenberg for comparison with sodar data. A square-shaped box pattern was flown at several altitudes. The flight legs of the box had a length of about one kilometer. In the afternoon of 13 October a flight from Falkenberg to Lindenberg was done at two altitudes and on 14 October, 2005, a flight was performed at Lindenberg for comparison with lidar data. An overview on the flights is given in table 1. A map showing the pattern of the second flight on 13 October, 2005, is shown in figure 5.

Date	Time (UTC)	Leg length	Altitude agl [m]
12 Oct.	14:30 - 15:00	1 km × 1 km	165, 220, 275, 330, 390
13 Oct.	12:10 - 12:45	1 km × 1 km	165, 220, 275, 330, 390 440, 495, 550
13 Oct.	15:00 - 15:30	1 km × 5 km	385, 440
14 Oct.	14:20 - 14:50	1 km × 1 km	330, 445, 560, 675, 780, 905

Tab. 1: 3D-box M²AV flights during launch-2005 experiment.

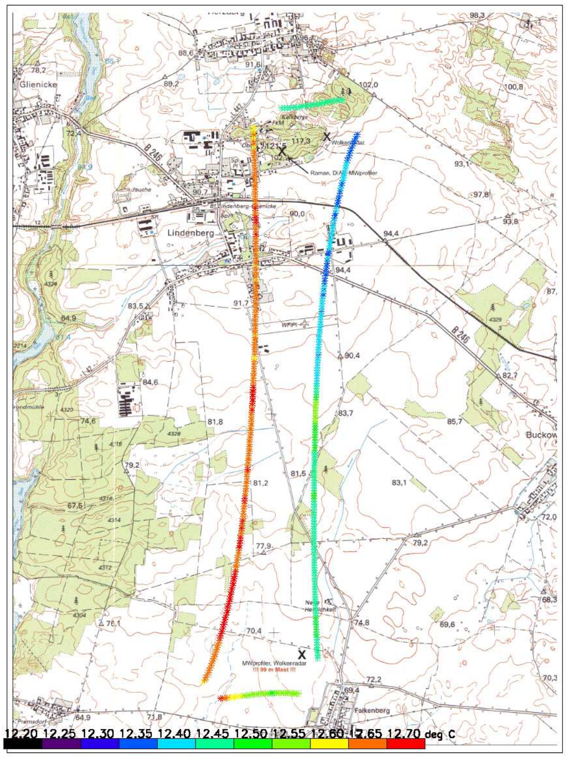

Fig. 5: *Flight pattern of the M²AV 1 km × 5 km box between Falkenberg and Lindenberg on 13 October, 2005. The color indicates the measured static temperature.*

On 27 January, 2006, the M²AV sensor package was mounted to the helicopter-borne turbulence probe Helipod (see figure 6). Due to a winterly weather situation the atmosphere was generally stably stratified and therefore large scaled turbulence was suppressed. Within small scaled turbulence the statistical errors of airborne measurements are less than under convective conditions (e.g. Bange and Roth, 1999). The smaller statistic uncertainties facilitate the identification of systematic measurement errors. The flight was performed near the research airport of Braunschweig, Germany. The flight pattern was a 5 km × 5 km square shaped box, flown at an altitude of about 800 metres above ground.

Fig. 6: *For a direct comparison of M²AV and Helipod data the M²AV electronics with the meteorological sensor equipment and the autopilot was mounted to the Helipod during a flight on 27 January, 2006.*

4. RESULTS

The database on 13 October, 2005, was suited for a comparison between the M²AV an the sodar. Figure 7 shows the virtual temperature measured by the sodar and the M²AV at different altitudes. The sodar temperature was provided by the MOL and was calculated using two different algorithms. One algorithm is the original algorithm of the sodar manufactor, the second algorithm was developed by the DWD. The virtual temperature is the temperature of dry air that has the same density as the measured, moist air. The comparison shows that the measured temperature agreed well with the sodar temperature calculated with the original algorithm. The sodar temperatures calculated with the DWD algorithm is about 0.8 K less.

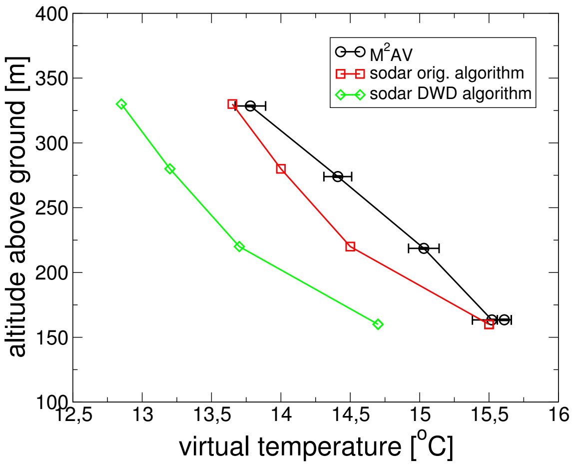

Fig. 7: *Temperature comparison between the M²AV and the sodar on 13 October, 2005, at the Falkenberg site.*

On 14 October, 2005, the M²AV performed measurements at the Lindenberg site to compare humidity data with the lidar. Figure 8 shows that the absolute humidity measurements of the M²AV agreed very well with the lidar data. The M²AV measurements show an absolute humidity only 0.3 g m^{-1} smaller compared to the lidar data. The conversion of this deviation to an error in relative humidity regarding the atmospheric conditions during the flight resulted in an error of about 2 % relative humidity. This is in agreement with the specifications of the Vaisala humidity sensor regarding the absolute accurracy of the humidity measurements.
From the direct comparison of the M²AV data with the calibrated data of the Helipod it was found that the temperature and humidity measurements agreed well.
At the time of the presented field experiments, the MAV autopilot did not provide heading data. As the knowledge of the true heading of the aircraft is essential for the determination of the horizontal wind vector components, these data were taken from the Helipod. All other navigation and air flow data which are necessary for the wind vector were used from the M²AV. It was found that the calculated wind components of the M²AV agreed well with the Helipod (see figure 9). For the horizontal wind components the deviation was less than one metre per second, and 1.5 m s^{-1} for the vertical speed. These deviations were mainly caused by the pendulum oscillation of the Helipod and will disappear when the M²AV is in autonomous operation. The

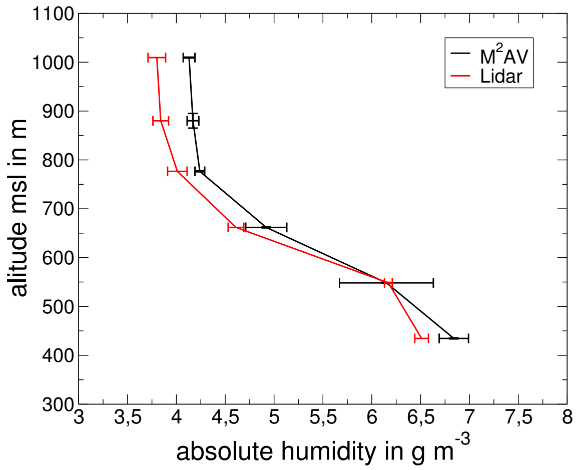

Fig. 8: *Absolute humidity comparison between the M^{2}AV and the lidar on 14 October, 2005, at the Lindenberg site. The M^{2}AV measurements are about 0.3 g m^{-3} less than the lidar data.*

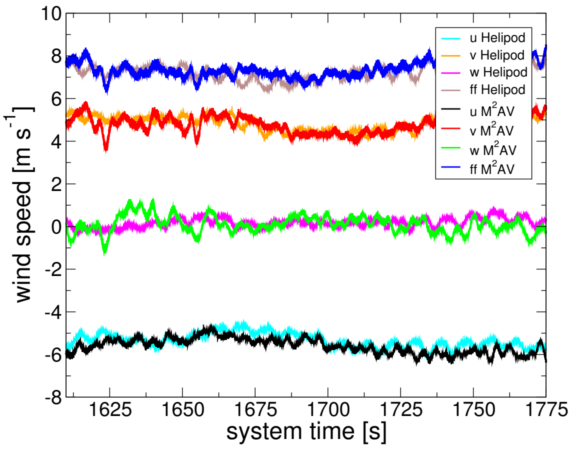

Fig. 9: *Time series of the M^{2}AV and Helipod wind vector components (u, v, w) and wind speed (ff) during a leg on 27 January, 2006. The mean values agreed well but the deviations are larger for the M^{2}AV.*

dynamic of the M^{2}AV is usually not as high as it was during the analysed flight.

The mean variance spectra of the three wind components are shown in figure 10. The Helipod pendulum oscillation is clearly visible with the maximum at 0.12 Hz. The sound of the helicopter's rotor blades caused some sharp peaks above 20 Hz. The slopes of the spectral densities agreed with the $k^{-\frac{5}{3}}$ law of the inertial subrange of atmospheric turbulence up to a frequency of about 10 Hz. With this and other analysis, it was found that the M^{2}AV is able to perform turbulence measurements. Taking the mean airspeed into account, turbulent structures of about two metres and larger were resolved.

5. OUTLOOK

For the M^{2}AV a new navigation system will be developed by the ILR before end of the year 2006. A cooperation with the British Antarctic Survey (BAS) will soon meet in a joint field experiment with M^{2}AVs, sodar, mast and a barograph array. A total of two M^{2}AV will perform measurement flights near the British antarctic station 'Halley' in the austral summer 2006/2007. Additional measurement flights are scheduled for the antarctic winter season 2007.

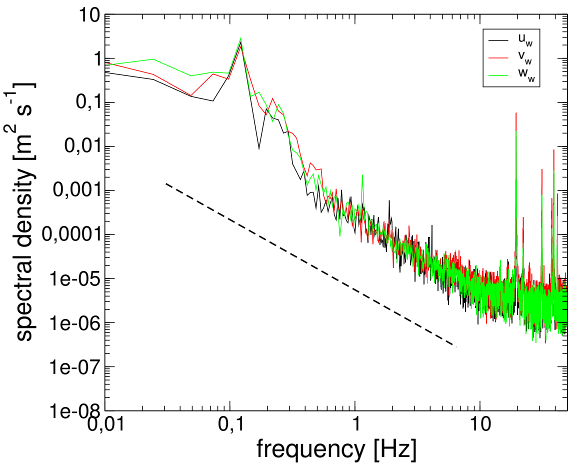

Fig. 10: *Mean variance spectrum of the M^{2}AV wind vector components during a single leg. The pendulum oscillation of the Helipod is the maximum at 0.12 Hz. Due to the missing anti-aliasing filters, the resolution was limited to 10 Hz.*

ACKNOWLEDGEMENTS

We are grateful to the Mavionics team who build the airframe and the autopilot module of the M^{2}AV.

For providing the sodar data we like to thank Dr. Frank Beyrich of the Meteorological Observatory Lindenberg of the German Weather Service.

Dr. Holger Linne of the GKSS research centre Geesthacht, Germany provided the lidar data. Many thanks to him.

The Helipod flights were performed by FJS

helicopter service, Damme, Germany. Thanks to the crew for their perfect flight operations.

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