Boundary layer measurements with the autonomous mini-UAV M^{2}AV

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1 Introduction

Aircraft measurements play an important role in boundary-layer research. The main advantage of airborne systems is their flexibility; capability of measuring on horizontal tracks or vertically probing the boundary layer by slant profiles. In the last ten years a new trend in the airborne meteorology evolves; the operation of Mini Unmanned Aerial Vehicle (UAV). The mini UAVs are inexpensive compared to a fully equipped research aircraft and highly flexible. The Meteorological Mini UAV 'M^{2}AV ' was developed at the Institute of Aerospace Systems (ILR) and build in cooperation with Mavionics GmbH, Braunschweig, Germany. The M^{2}AV is an autonomous UAV for meteorological measurements in the boundary layer (Fig. 1). The meteorological sensors are mounted on the nose boom and include two temperature sensors, a humidity sensor and a five-hole probe (5HP). A GPS receiver and a Inertial Measurement Unit (IMU) are on board to measure the groundspeed and the attitude of the aircraft. The first meteorological performance was during the LAUNCH-05 field experiment at the Meteorological Observatory Lindenberg (MOL) of the German Meteorological Service (DWD) (Spieß *et al.*, 2007). Temperature and humidity measurements were compared with the remote-sensing systems sodar/RASS and a differential absorption lidar. The first comparable wind measurements were carried out in August, 2007 at the MOL during a short campaign. The 99m-tower and sodar measurements of the DWD were used for comparison with the M^{2}AV .

A long term co-operation between the ILR and the British Antarctic Survey (BAS) was established in 2005. A joint project was the deployment of one M^{2}AV to Halley station for the southern summer 2005/2006. Two additional systems and one researcher of ILR were sent in the southern summer 2006/2007 to Halley station.

Figure 1: *M^{2}AV system at Antarctica*

2 M^{2}AV system

The M^{2}AV is controlled by an on-board autopilot system which communicates with a ground station (laptop PC) for the exchange of measured data and flight-mission updates like new way-points. The aircraft can be hand-launched or started with a bungee rope. After the start the way-point navigation is activated. A laptop is used to follow the aircrafts mission and to check (meteorological) parameters which are send from the aircraft to the laptop using telemetry. During the flight the mission can be altered e.g. by sending new way-points to the aircraft. The landing procedure can be done automatically or manually. The detailed specifications were published by Buschmann *et al.* (2004) and Spieß *et al.* (2007) and a summary is listed in Tab. 1.

Figure 2: *M^2AV meteorological measurement sensors.*

2.1 Autopilot system

The current flight-guidance algorithm uses discrete way-points to define the flight path. While this approach is a simple and robust solution, it lacks predictability and reliability in terms of flight trajectory accuracy: the aircraft will conduct more or less unpredictable maneuvers upon reaching a way-point due to the sudden change in commanded ground track. In addition, wind and gusts can lead to comparably large deviations between the flight path defined with the mission planning software and the actually flew trajectory even if the way-points are only a few hundred meters apart. While this behaviour is not critical in terms of flight safety in itself, it makes mission planning and aircraft operation for low level flights with obstacles like wind power plants impossible or irresponsible. A practical but somewhat inelegant solution is the use of additional way-points even along straight legs. To overcome this problem, a complete new flight guidance and control algorithm is currently being implemented: Instead of defining single GPS way-points, the user defines cubic splines to determine the flight trajectory. This ensures deterministic curve radii between spline segments and allows for easy definition of complex flight patterns. At first flight tests, the new spline trajectory controller was able to minimise the distance from the aircraft to the planned trajectory to better than 3 m horizontally and 5 m vertically. While these flight tests were conducted at moderate conditions (5 m s^{-1}mean wind speed, gusts up to 8 m s^{-1}), the first evaluations promised very satisfying capability also under harsh conditions.

2.2 Meteorological sensor package

The meteorological package includes of one fast temperature sensor (thin foil element) developed by Dantec, a Vaisala Intercap (HMP50) which measured the temperature and relative humidity with a response time (in flight) of 1 s (Fig. 2). Both temperature signals are combined using a complementary filter and results in one temperature series with a resolution of 30 Hz. A 5HP manufactured by the Institute of Fluid Dynamics (TU Braunschweig) measures five differential pressures at the tip of the probe. The static pressure is measured by the four holes at the side of the probe. The measurements are used to calculate the airflow angles and the dynamic pressure. The micro-electromechanical system sensor system (MEMS) gives time series of the angle accelerations and the accelerations in *x*, *y* and *z* direction and has been developed at ILR. The sensor block contains a 3-axis-IMU. The design consists of three angular rate sensors with a range of $\pm 300^\circ s^{-1}$ and two accelerometers with two axes each, providing redundancy for the aircrafts longitudinal axis. The range is 2 *g* for the horizontal and 10 *g* for the vertical axis. The IMU has a weight of less than 15 gram and a size of 40x40x16 mm^3. The IMU was calibrated for the determination of the scale factor, bias and misalignment (Buschmann *et al.*, 2006). The temperature influence on calibration data was not explicitly taken into account. But due to the integration with GPS, changes in sensor bias can be estimated by the navigation filter and extracted from the measurements. Drive tests and flight have shown biases of $0.1 - 0.15$ ms^{-2} and $0.6 - 2.3^\circ$ s^{-1}. The ground speed vector and the position is measured by a single-antenna single-frequency GPS receiver (μ-blox company, type SAM LS) with a measurement frequency of 1 Hz. Except for the GPS receiver, all meteorological sensors are sampled with 100 Hz.

Since the LAUNCH-05 experiment (Spieß *et al.*, 2007) the wind vector measurement has improved. The reliable determination of attitude, velocity and position of the aircraft is essential for wind identification. This is achieved by an integrated navigation system consisting of GPS and IMU. The system offers a significantly increased performance due to the complementary characteristics of GPS and IMU, where the latter assures the continuous availability attitude, velocity and position. The growth of navigation errors with time due to the low cost MEMS IMU is prevented by the use of aiding information provided by

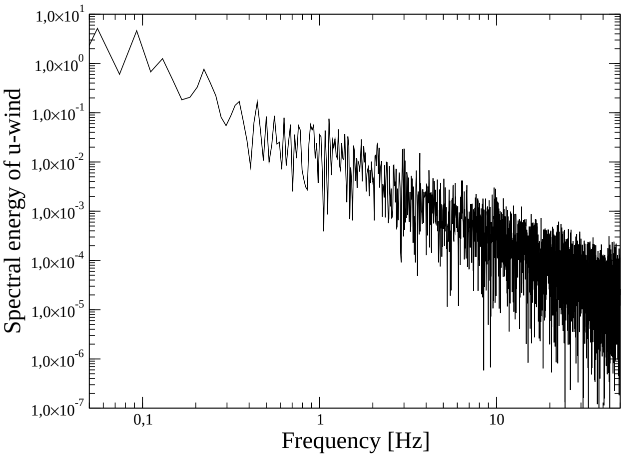

Figure 3: *M^2AV Example of a variance spectra of the u-wind component, measured by the M^2AV on 2 August, 2007.*

Table 1: *Specification and performance of the M^2AV.*

Take off weight	6 kg
Wing span	2 m
Twin engine	electric propulsion
Navigation	GPS, IMU
Optimal speed	21-24 m s^{-1}
Max. climbing rate	5 m s^{-1}
Endurance	$<$60 min
Altitude range	10-800 m AGL

the GPS receiver. For GPS/IMU integration a discrete error state Kálmán Filter was used. Detailed information on this filter method applied on a MAV is published by Winkler and Vörsmann (2007). Combined with the measurement data from the 5HP the M^2AV is capable of calculating the wind vector with 30 Hz which represents a resolution of less then 1 m (Fig. 3).

3 M^2AV at Halley station, Antarctica

Since 2005 M^2AV are in deployment at Halley V on the Brunt Ice Shelf in the Weddell Sea of Antarctica. The surrounding area of Halley is flat ice and the station is located in an ellipse of the coastline, about 15 km for the coast to the north, west and south-west. At Halley several experiments are carried out continously. Ozone and other trace gases are measured at the clean air sector laboratory (CASLab). A single axis vertically pointing acoustic sounder (sodar) measures the acoustic backscatter in the atmosphere up to 500 m. Turbulence measurements are performed at several heights on a 32 m mast close to the CASLab and further standard meteorological measurements in 2 m and 10 m are taken at the main station. Radio sondes are launched once per day and in springtime further basic meteorological and ozone data are taken occasionally using a thetered balloon.

3.1 Research goals, BAS

To have confidence in predictions of future climate change requires an understanding of how the Earth's climate system actually works. At present our understanding is far from complete, with notable knowledge gaps in the polar regions and in the interactions between component parts of the climate system.

The Halley based UAV project addresses one facet of these deficiencies, wintertime air-sea-ice fluxes, and the formation of Antarctic Bottom Water (AABW).

The production of AABW, a cold oxygenated water mass that spreads across much of the floor of the World Ocean, is a key element of the global climate system. Its production is important for two reasons: it cools and ventilates the deep ocean, which has relevance for marine life and its effect on sea level; and it is believed to be a driver in the global thermohaline circulation. However our understanding of the processes that play a role in its formation, including factors affecting the surface radiation balance and the production of sea ice, are poor.

Wintertime observations of fluxes over the sea-ice zone are challenging, and require either an ice-bound ship, or instrumented aircraft. Very few such high quality observations exist due to the expense and risk of using large infrastructure in harsh conditions. For example, although data are available from the BAS instrumented manned aircraft flights from autumn (e.g. March), and spring (e.g. October) (King *et al.*, 2007), these are at the limits of possible BAS aircraft-based fieldwork (Renfrew *et al.*, 2002). To augment these data, and assess fluxes during the depths of winter, BAS uses the relatively inexpensive and low (human) risk UAV.

3.2 Research goals, ILR

An exquisite experimental site for the undisturbed observation of the stable boundary layer (SBL) is the very flat ice shelf (with a slope of 1:2000) around the Halley station of BAS. Here no disturbance due to orography is expected. Several field studies using ground-based and remote-sensing systems and also tethered kites were already performed and a wide data base is available. The M^2AV flight measurements and the already available data base at Halley station will be analysed to determine the fine structure of the SBL i.e., layers, sheets, fossil turbulence, intermittent turbulence and waves – and the influence of a low level jet on these processes.

The most important instruments at Halley in this context are the sodar, the 32 m mast and the M^2AVs. While the first two systems provide long-term vertical soundings, the latter is applied for short-term (one hour) *in situ* sampling. Using M^2AV systems, area-representative mean values of temperature, wind vector and humidity can be determined on horizontal box flight patterns at several altitudes within the atmospheric boundary layer. Applying inverse models on these data, the flux divergence and the horizontal transport (advection) through these flight boxes can be calculated. The use of structure functions, multi-resolution co-spectra and wavelet analysis give information on the spectral characteristics of turbulent structure and transport of the layered SBL. Topics like the observed temporal variation in the sodar backscatter and the area-representivity of the sodar and the tower will be analysed using the M^2AV *in situ* measurements.

3.3 Modifications for the extreme Antarctic conditions

In order to fulfil both BAS and ILR research goals, the M^2AV flights at Halley station needed intense preparations before and during the actual experiment time. M^2AV flights will be performed directly at Halley station in the south east of the CASLab within the clean air sector. For the on-base operations a ground station on the Simpson platform needed to be set up. The ground station operator must have permanent communication ability to the M^2AV operator (safety pilot). To do so a VHF communication system between the platform and the M^2AV launch site was developed and deployed.

BAS purchased a new Tucker Teracat, a QSB 5.9 litre Cummins powered Sno-Cat to be a mobile flying operations room. The Sno-Cat was modified by BAS's Vehicle Section, and was equipped with generator, computer ports and power supply, heaters, GPS for navigation to the flight sites and fittings and power supply for the M^2AV ground station telemetry. The Sno-Cat became a complete ground station and set up workshop for the M^2AV .

After the first test flights it came out that also modifications of the general M^2AV equipment itself were necessary. For instance the bungee rubber that is used for launching the M^2AV which works fine in European winters did not provide sufficient thrust in the colder temperatures at Halley. To protect the bungee from the cold, several tests were made and finally two bungees were connected in series. Additionally both rubbers were insulated with a plastic tube sheath. Due to the wrapping of the bungee it was kept warm during the outside preparations of the M^2AV before launch. It then provided enough power to launch the M^2AV safely.

Also special care had to be taken on the M^2AV batteries. Although modern Lithium Polymer (LiPo) batteries are used which can withstand cold temperatures much better than non-Lithium batteries the batteries also loose up to half of their capacity when completely frozen at -20^oC. At lower temperatures the loss of power can get even worse. In order to minimise the risk of losing an aircraft due to a power failure, the batteries are pre-warmed before flight. During the flight the power drain from the batteries result in a certain self heating effect which also contributes to the possible flight durations. Furthermore the M^2AV was equipped with a small data logger to record the battery. The data can be used to estimate the maximum flight duration with respect to the ambient temperature conditions. For the meteorological sensors the power supply was modified so that even at temperatures of -30^oC a constant voltage is guaranteed.

The scientific projects also required some modification of the sensor set. In order to determine the edge between sea ice and open water or newly formed ice, the M^2AV meteorological sensor set was expanded with an infra red (IR) surface temperature sensor. The 'Convir MLE series' of IR sensors made by 'Calex Electronics Limited' company, England used. The sensor range was adjusted to the requirements at Halley by the manufactor. Some modifications were done at Halley in order to minimise the weight of the sensor and to connect it easily to the meteorological data acquisition system.

3.4 Implementation of Ozone sensor

The occurrence of ozone depletion events (ODEs) in the polar boundary layer is known since 25 years. The events were observed in coastal sub-Arctic, Arctic and Antarctic regions. During a depletion event the ozone concentration drops from a normal concentration around 30 ppbv to lower concentrations and can even reach values less than 1 ppbv.

At Halley station regular ozone measurements are made at the CASLab since 2003. The ozone data taken at Halley in austral springtime showed ODEs with significant (and sometimes very rapid) loss in ozone concentration (Jones *et al.*, 2006). In addition to the CASLab measurements, ozone measurements using a tethered balloon or tethered kite were first made in 2004. The tethered balloon ozone measurements were then regularly taken since austral spring 2005 during ODEs. In 2007 another ozone measurements system will be set up close to the coast at Precious Bay. Powered by a set of three wind turbines, ozone measurements will be taken continously at surface level. The CASLab, Precious Bay and balloon measurements however also have restrictions as they are dependent on the mean wind speed to cover a certain fetch. Furthermore, they are only point measurements or very limited two dimensional measurements of the balloon, respectively. In austral spring 2007 it is intended to make usage of the M^2AV s at Halley station and off base close to the coasts (e.g. Precious Bay) to take ozone measurements. The data shall contribute to determine the horizontal and vertical extend of the ODEs. The coastal flight measurements might also contribute to the determination of the source of the halogens. The combination of all data sources will provide a good data base for further analysis of ODEs.

As only two aircraft are equipped with the meteorological sensor set, the intention was to use the third aircraft with an ozone sensor. For this task a sensor based on tungsten trioxide (WO_3) semiconductor is used for ozone monitoring which is described in Utembe *et al.* (2006). The sensor was developed for use with radio sondes or tethered sondes and therefore designed and calibrated for a flow speed of about 5 m s^{-1} through the sensor. As the M^2AV has an optimal flight speed of 22 m s^{-1} , a flow speed reducer must be implemented to slow the airspeed down to 5 m s^{-1}. Additionally, the printed circuit board (pcb) to which the sensing element is attached was enclosed in a stream line form. This reduced the vibrations of the sensor in the flow significantly and therefore reduces the risk of damaging the pcb. The ozone sensor was equipped with its own power supply and data storage. The ozone sensing system had a final weight of only 360 g including the data logger with its power supply, ozone sensor, sensor electronics and power its supply.

3.5 Flights

For the summer 2007 an intense test program with the M^2AVs was planned. The goal was to be ready for autonomous meteorological measurement flights over coastal sea ice off base before end of February 2007. Unfortunately, this goal was not achieved. First of all, the ship arrived late at Halley. The relief of the ship was finished on 10 January, about 10 days later than planned. After intense preparations the first M^2AV flight was performed on 16 January about 5 km to the west off base. The flights in January led to modifications which were necessary to adapt the M^2AV to the extreme conditions in Antarctica.

For February and March 2007 it was planned to perform an average of two or three flights per week and the first meteorological measurements at the end of February. Unfortunately, bad weather conditions reduced the amount of flights. The M^2AVcan not operate properly at high wind speed (above 12 m s^{-1}). At wind speeds of more than 12 m s^{-1} , the flights start to be unsteady and very un-economic. For our missions the wind speed limit at the ground was set to 5 m s^{-1}, expecting up to 10 m s^{-1}in greater altitudes. Good visibility and contrast during the flight is needed for the start and landing procedure performed by the safety pilot. Only three flights were performed in February due to high wind speeds and bad visibility and contrast conditions. A field safety training of the M^2AV pilot and ground station operator in the beginning of March made flights during this time impossible. Apart from that the weather conditions again prohibited flight operations. Either cold temperatures of nearly -30^oC or high wind speeds made flights impossible. The temperature limit at surface level for M^2AV flights was set to about -28^oC. The battery capacity drops a lot at these cold temperatures and make flights uneconomic. These cold and windy weather conditions basically also made flights after March and in the winter impossible.

Summarising, the bad weather conditions at Halley in Summer and autumn 2007 led to much less M^2AV flights than expected and planned. This resulted in no meteorological data from the M^2AV flights during this

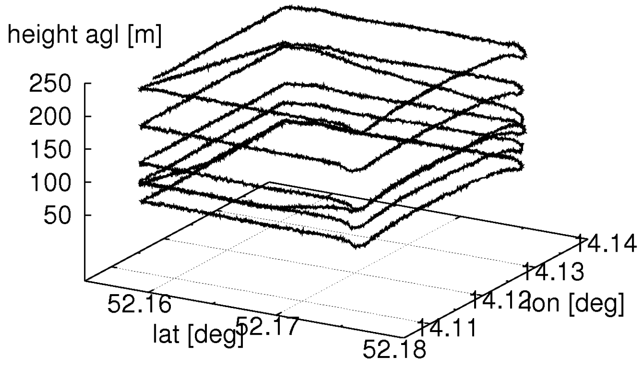

Figure 4: *The 3D-box pattern flown on August, 2, 2007 at MOL. This example impressively demonstrates the ability of the M*^{2}*AV to keep altitude and track.*

period.

For the austral spring and beginning summer 2007/2008 the re-start of flight operations are planned as soon as the weather conditions allow flights. Ozone concentration and meteorological measurement flights are expected to be performed on and off-base the Halley station.

4 Results

For preparation and support of the Antarctical flight missions and to obtain more experimental experience with the M^{2}AV a field campaign was carried out in the beginning of August, 2007. The boundary layer measurement field of the DWD was chosen as the location for the experiment. This measurement field is located 5 km south of the observatory, near Falkenberg and was also used for start and landing of the M^{2}AV . The lower part of the boundary layer was probed by a 99m-tower, 12 m tower and a sodar/RASS. A Large Aperture Scintillometer (LAS) was installed over a path length of 4.7 km. The LAS transmitter was installed at the 99m-tower in Falkenberg ant the receiver on a 30m-lattice tower at the MOL observatory site.

The main goal was the comparison of the M^{2}AV wind measurements with tower and sodar measurements. The 99 m high measurement tower provided measurements of temperature, humidity and wind speed on four levels (40, 60, 80, 98 m). The wind direction was measured at 40 and 98 m height. The sodar wind speed and wind direction profiles reached upto 350 m above ground. The sodar/RASS temperature profiles gave the virtual temperature upto a level of 200 m above ground. Unfortunately, the RASS temperature profile measurements were of poor quality due to the atmospheric backscatter conditions, they are not used in the present analysis.

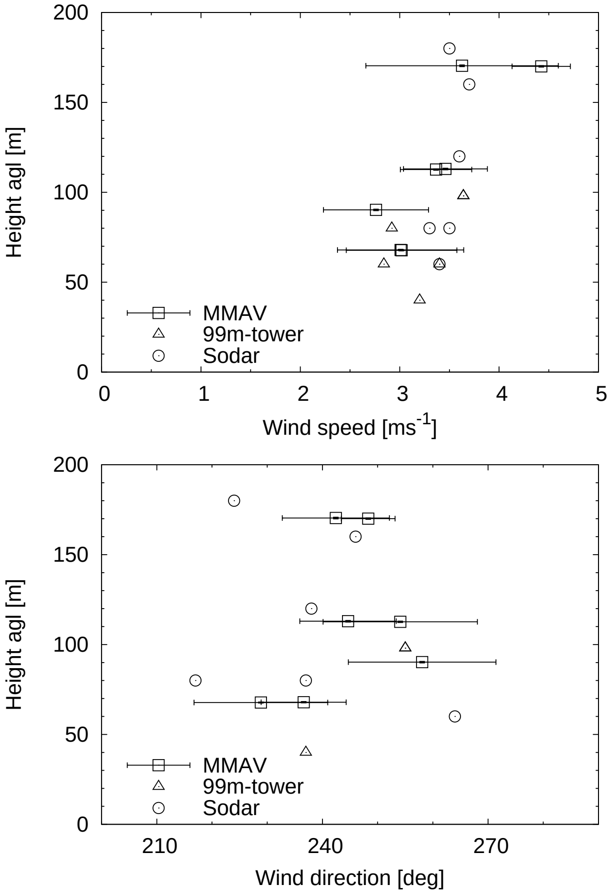

Figure 5: *Wind speed and wind direction. First 3D-box flight performed on 1 August, 2007 between 9:22 and 9:52 UTC. The M*^{2}*AV data at the same height were measured during two consecutive square-shaped flight patterns. The error bars represent the standard deviations of the M*^{2}*AV measurements (Tab. 2). For every M*^{2}*AV time interval and height the corresponding tower (10 min average) and sodar (15 min average) measurements were plotted.*

During the 2-days experiment, six M^{2}AV flight (including two 3D-box patterns) were performed. The 3D-box patterns consisted of several square-shaped patterns (4 legs) flown around the 99m-tower at different heights (Fig. 4). Seven square patterns (with flight legs of 650 m) in four flight levels (170, 113, 90 and 68 m agl) were flown during the first 3d-box. The second 3D-box consisted of five square patterns (with legs distance of 1600 m) in five different heights (230, 173, 115, 87 and 58 m agl). Since the 3D-box flights give information of the vertical structure of the boundary

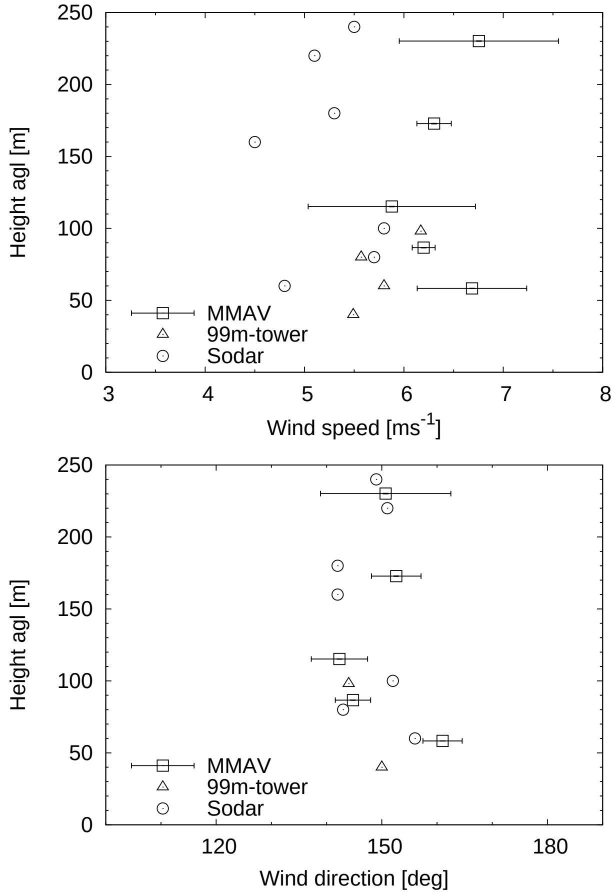

Figure 6: *Wind speed and wind direction measured on 2 August, 2007 between 8:37 and 9:15 UTC. The error bars represent the standard deviations of the M^{2}AV measurements (Tab. 2).*

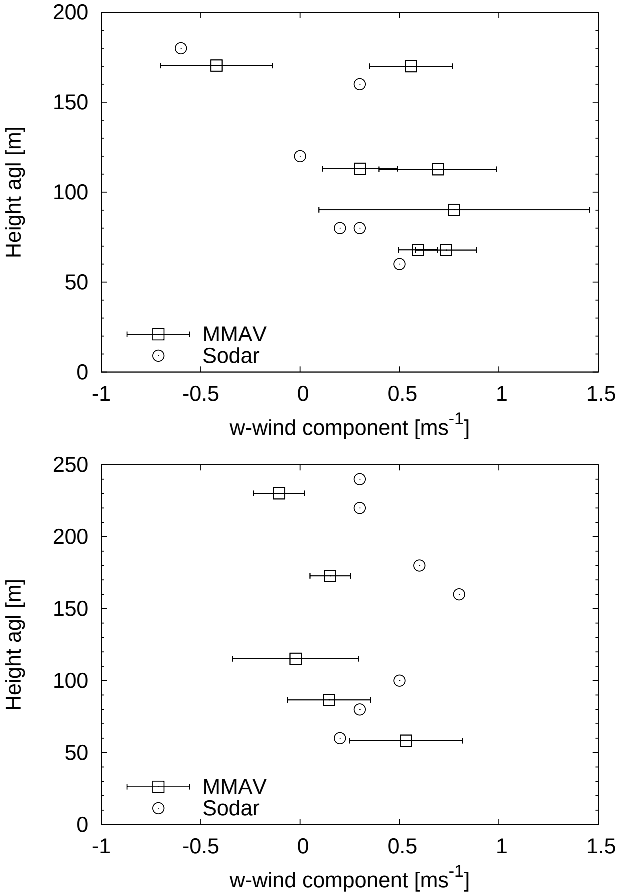

Figure 7: *Vertical wind, the error bars represent the standard deviations of the M^{2}AV measurements (Tab. 2). Top: first box flight, 1 August, Bottom: second box flight on 2 August.*

layer, these measurement flights are compared with the 99m-tower and sodar profiles.

4.1 Wind

The wind measurements were averaged over the four legs which gave a mean values for every square-shaped pattern (see Tab. 2). The averaging lengths of 650 m for the first flight and 1600 m for the second flight were probably too short to obtain small statistical errors especially in convection.

The M^{2}AV wind measurements were compared with tower and sodar measurements. For each square-shaped pattern the corresponding tower (10 min average) and sodar (15 min average) measurements at about the same height were selected (Tab. 2, Fig. 5 and 6).

On the first flight (Fig. 5) the horizontal wind was weak, 3…4 m s^{-1}. Compared to the sodar and the tower measurements, the M^{2}AV horizontal wind speed measurements agreed well, within 1 m s^{-1}. On the contrary the wind direction showed larger deviations compared to particularly the sodar data (deviations within 20 deg). A stronger wind speed was measured on the second flight (Fig. 6). In general the M^{2}AV measured a larger wind speed compared to the sodar and tower measurements. The M^{2}AV wind direction agreed well with the sodar and tower data. Compared to the first flight smaller standard deviations were found for the wind direction.

The mean vertical wind measured by the M^{2}AV was accompanied by large standard deviations upto 0.7 m s^{-1} (Fig. 7). Nevertheless, the vertical wind measurements on both flight days agreed with the sodar measurements within their statistical uncertainty.

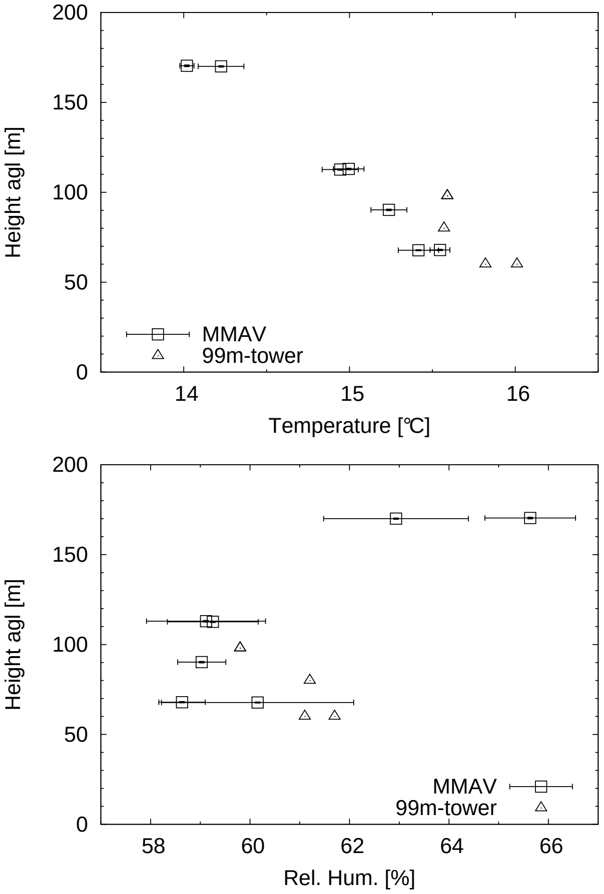

Figure 8: *Temperature an relative humidity measured on the first box flight, 1 August, 2007.*

4.2 Temperature and humidity

During the LAUNCH-05 campaign M^{2}AV temperature and humidity measurements were performed at the MOL site (Spieß *et al.*, 2007). The absolute humidity was found a comparable (within 0.3 g m^{-3} or 2%) to the lidar measurements provided by MOL. During the last experiment at the MOL site (August, 2007) no lidar was available. The relative humidity and the temperature were compared with tower measurements (Tab. 3). Figures 8 and 9 shows the temperature measurements. For both flights the M^{2}AV measurements agreed well with the tower data. Both systems showed a temperature decrease in height, which was expected in a convective boundary layer.

In general the M^{2}AV humidity measurements were smaller compared to the corresponding tower measurements (Fig. 8 and 9). The differences between M^{2}AV and tower measurements were less then 3% for the first flight and less then 1% for the second flight (which was comparable with the LAUNCH-05 results Spieß *et al.* (2007)).

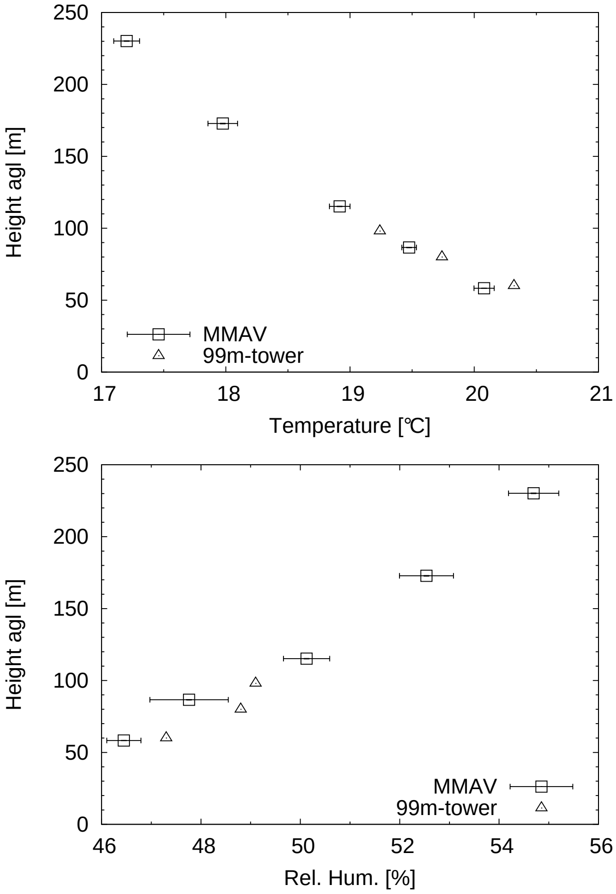

Figure 9: *Temperature an relative humidity measured on the second box flight, 2 August, 2007.*

5 Conclusions

The first comparison of the wind measurements with the autonomous M^{2}AV showed a satisfying result. Despite the short averaging length of the M^{2}AV data in a convective boundary layer, the wind was determined comparable to the tower and sodar data at the MOL site. Particular for the first flight with weak wind conditions, the differences with sodar and tower were less then 1 m s^{-1}. For stronger wind conditions, the M^{2}AV measured higher horizontal wind speeds compared to the sodar profiles (differences within 2 m s^{-1}). The temperature and humidity measurements agreed well with the tower measurements.

Due to the bad weather condition at Halley last southern summer and autumn, less M^{2}AV missions were performed as planned. The flight operations will be restarted as soon as the weather conditions change. Meteorological measurements and flights with the ozone sensor are scheduled for the southern spring and summer 2007/2008.

Table 2: *Box patterns flown around the 99 m-tower. The horizontal wind speed* U_{hor}*, the wind direction* Ω_{hor} *and the vertical wind* w *are listed for every box.* σ *represents the standard deviation of the measurements. The sodar and tower measurements are written in the same row as the compared* M^2AV *data.*

	M^{2}AV				Sodar				99m-Tower		
flight/ leg	z m	U_{hor} (σ) m s^{-1}	Ω_{hor} (σ) deg	w (σ) m s^{-1}	z m	U_{hor} m s^{-1}	Ω_{hor} deg	w m s^{-1}	z m	U_{hor} m s^{-1}	Ω_{hor} deg
1/01	170	3.63 (1.00)	242.4 (9.7)	-0.42 (0.28)	160	3.7	246	0.3			
1/02	170	4.42 (0.29)	248.3 (4.9)	0.56 (0.21)	180	3.5	224	-0.6			
1/03	113	3.46 (0.42)	244.6 (8.7)	0.30 (0.19)	120	3.6	238	0.0	98	3.7	255
1/04	113	3.37 (0.36)	254.1 (14.0)	0.69 (0.30)	120	3.6	238	0.0	98	3.7	255
1/05	90	2.76 (0.53)	258.1 (13.4)	0.78 (0.68)	80	3.3	237	0.2	80	2.9	
1/06	68	3.02 (0.56)	228.9 (12.1)	0.73 (0.15)	60	3.4	264	0.5	60	2.8	
1/07	68	3.01 (0.64)	236.6 (7.7)	0.59 (0.10)	80	3.5	217	0.3	60	3.4	
1/07									40	3.2	237
2/01	230	6.75 (0.80)	150.7 (11.8)	-0.11 (0.13)	220	5.1	151	0.3			
2/01					240	5.5	149	0.3			
2/02	173	6.30 (0.17)	152.6 (4.5)	0.15 (0.10)	160	4.5	142	0.8			
2/02					180	5.3	142	0.6			
2/03	115	5.88 (0.84)	142.3 (5.1)	-0.02 (0.32)	100	5.8	152	0.5	98	6.2	144
2/04	87	6.20 (0.12)	144.8 (3.2)	0.15 (0.21)	80	5.7	143	0.3	80	5.6	
2/05	58	6.68 (0.55)	161.0 (3.6)	0.53 (0.28)	60	4.8	156	0.2	60	5.8	
2/05									40	5.5	150

Table 3: *Temperature and humidity measurements of the* M^2AV *compared to tower and sodar data. Temperature* T*, relative humidity* RH*, mixing ratio* m *and height above ground* z*.*

	M^{2}AV				99m-Tower		
flight/ leg/	z m	T (σ) °C	RH (σ) %	m (σ) g kg^{-1}	z m	T °C	RH %
1/01	170.4	14.08 (0.04)	65.63 (0.91)	6.76 (0.09)	-	-	-
1/02	170.0	14.28 (0.14)	62.93 (1.46)	6.57 (0.14)	-	-	-
1/03	113.0	15.05 (0.09)	59.11 (1.20)	6.45 (0.10)	98	15.65	59.8
1/04	112.7	15.00 (0.11)	59.25 (0.91)	6.45 (0.06)	98	15.65	59.8
1/05	90.2	15.30 (0.11)	59.03 (0.48)	6.52 (0.04)	80	15.63	61.2
1/06	67.8	15.48 (0.12)	60.15 (1.93)	6.71 (0.19)	60	15.89	61.1
1/07	67.9	15.61 (0.06)	58.63 (0.47)	6.59 (0.06)	60	16.08	61.7
1/01	230.1	17.27 (0.10)	54.70 (0.51)	7.00 (0.07)	-	-	-
1/02	172.8	18.05 (0.12)	52.54 (0.54)	7.02 (0.06)	-	-	-
1/03	115.2	19.00 (0.08)	50.13 (0.47)	7.06 (0.04)	98	19.32	49.1
1/04	86.6	19.56 (0.060)	47.76 (0.79)	6.94 (0.10)	80	19.83	48.8
1/05	58.3	20.16 (0.08)	46.45 (0.34)	6.98 (0.05)	60	20.41	47.3

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