SUMO: A Small Unmanned Meteorological Observer for atmospheric boundary layer research

Article *in* IOP Conference Series Earth and Environmental Science · May 2008

DOI: 10.1088/1755-1315/1/1/012014

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Meteorologische Zeitschrift, Vol. **18**, No. 2, 141-147 (April 2009)

Open Access Article

The Small Unmanned Meteorological Observer SUMO: A new tool for atmospheric boundary layer research

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(Manuscript received September 9, 2008; in revised form February 5, 2009; accepted February 6, 2009)

Abstract

The Small Unmanned Meteorological Observer SUMO has been developed as a cost-efficient measurement system with the aim to close the existing observational gap of atmospheric measurement systems in between meteorological masts/towers and radiosondes. The system is highly flexible and has the capability for in-situ ABL measurements with unique spatial and temporal resolution. SUMO is based on a light-weighted styrofoam model airplane, equipped with an autopilot system for autonomous flight missions and in its recent version with meteorological sensors for temperature, humidity and pressure. With its wingspan of 80 cm, its length of 75 cm and a total lift-off weight of 580 g, SUMO is easy to transport and operate even in remote areas with limited infrastructure. During several field campaigns in 2007 and 2008 the system has been successfully tested and operated. Atmospheric profiles of temperature, humidity, wind speed and wind direction have been determined up to 3500 m above ground during the FLOHOF (FLOw over and around HOFsjökull) field campaign in Central Iceland in July/August 2007. During a 3 week campaign on and around Spitsbergen in February/March 2008 the SUMO system also proved its functionality under polar conditions, reaching altitudes above 1500 m even at ground temperatures of –20°C and wind speeds up to 15 m s^{-1}.

Zusammenfassung

SUMO (Small Unmanned Meteorological Observer) wurde mit dem Ziel entwickelt, ein kostengünstiges Messsystem für die atmosphärische Grenzschicht zur Verfügung zu stellen, das die bestehende Beobachtungslücke zwischen meteorologischen Masten und Radiosonden schliessen kann. Das System ist äußerst flexibel und ermöglicht in-situ Grenzschichtmessungen mit hoher zeitlicher und räumlicher Auflösung. Ein leichtes Modellflugzeug aus geschäumtem Kunststoff bildet die Grundstruktur von SUMO. In seiner aktuellen Version ist SUMO mit meteorologischen Sensoren für die Messung von Temperatur, Feuchte und Druck ausgestattet. Ein Autopilot-System ermöglicht einen weitgehend autonomen Einsatz. Mit einer Länge von 75 cm, einer Spannweite von 80 cm und einem Gesamtgewicht von 580 g ist SUMO auch in abgelegenen Regionen mit eingeschränkter Infrastruktur leicht einsetzbar. Das System wurde 2007 und 2008 im Rahmen von mehreren Messkampagnen erfolgreich geflogen. Im Rahmen des Experimentes FLOHOF (FLOw over and around HOFsjökull) auf Island konnten mit SUMO Grenzschichtprofile bis in eine Höhe von 3500 m über Grund gemessen werden. Während einer 3-wöchigen Messkampagne auf und um Spitzbergen im Februar/März 2008 bewährte sich das System auch unter arktischen Bedingungen. Bei Temperaturen von –20°C und Windgeschwindigkeiten bis zu 15 m s^{-1} konnten die Grenzschichtprofile bis zu einer Höhe von 1500 m über Grund bestimmt werden.

1 Introduction

The three-dimensional structure of the atmospheric boundary layer (ABL) is the key for the understanding of surface-atmosphere exchange processes (e.g. STULL, 1997). Further improvement of this understanding requires a combination of fine-scale modeling efforts and innovative measurement strategies based on high resolution observations in space and time. The availability of corresponding measurement systems will be crucial e.g. for the validation of fine scale numerical simulations and the test and improvement of the underlying boundary layer parameterization schemes and thus for future progress both in numerical weather prediction and in climate modeling (e.g. STENSRUD, 2007). Moreover such a system will facilitate novel measurement approaches directed toward poorly understood ABL phenomena as stable boundary layers or entrainment processes.

Unmanned aerial systems (UAS) have an enormous potential to close the existing gap of in-situ ABL observations covering horizontal scales from several tenth of meters up to more than 10 km. First attempts on the basis of remotely controlled small unmanned aerial vehicles (SUAVs) have been started some decades ago (KONRAD et al., 1970), and the systems have gradually been improved. A corresponding profiling system (KALI) has for example been developed at the University of Munich, Germany. During several field campaigns in Nepal, Bolivia and Germany atmospheric profiles of pressure,

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DOI 10.1127/0941-2948/2009/0363

0941-2948/2009/0363 $ 3.15

temperature and humidity could be determined up to 3 km above ground (e.g. EGGER et al., 2002; EGGER et al., 2005).

The two main shortcomings of that system have been the need of experienced pilots for remote control of the SUAV and the lack of an appropriate wind measurement system. During the last years substantial progress in the field of miniaturization of electronic components has been achieved. As a consequence, miscellaneous autonomous SUAV systems, mainly used as drones for military reconnaissance purposes, have been developed. Recent attempts to adapt this new technical potential for atmospheric measurements show promising results (HOLLAND et al., 2001; MA et al., 2004; SPIESS et al., 2007).

These systems, with weights between 10 and 50 kg and a wingspan in the order of 2–3 m need substantial infrastructure for operation. In addition, the costs for fully equipped meteorological versions are in the order 50–100 kEuro per unit. The Small Unmanned Meteorological Observer (SUMO) has now been specifically designed as 'recoverable radiosonde' for atmospheric boundary layer research. The aim was to develop a mobile, flexible and cost-efficient platform (below 3 kEuro per unit) for the determination of temperature, humidity, and wind profiles that can be utilized without extensive infrastructural requirements in remote areas and under harsh environmental conditions. In this paper a technical description of the SUMO system will be presented together with first results of several measurement campaigns for the documentation of the wide range of future applications.

Figure 1: The SUMO airframe based on the model airplane construction kit FunJet by Multiplex and the laptop used as ground control station.

Table 1: Technical key parameters of the FunJet airframe used as SUMO platform.

length	75 cm
wingspan	80 cm
weight	580 g
average air speed	12–18 m s^{-1}
maximum air speed	35 m s^{-1}
average ascent rate	7–10 m s^{-1}
maximum ascent rate	15 m s^{-1}
maximum altitude above ground	3.5 km
endurance	up to 30 min

2 The SUMO system

In its recent version, SUMO is based on a commercially available model plane construction kit, equipped with an open-source autopilot system and meteorological sensors for the measurement of temperature, humidity and pressure. Figure 1 shows the aircraft and the laptop used as ground control station for flight mission planning and in-flight control of the SUMO system.

2.1 Airframe

The presented prototype of SUMO is based on the FunJet construction kit manufactured by Multiplex. It is a delta-wing pusher prop jet composed of expanded propylen (EPP), a lightweight foam material. The aircraft is electrically powered by a brushless motor (AXI 2212/26) driving a 9"x 6" air-screw. A lithium polymer (LiPo) battery pack with a capacity of 2100 mAh enables a flight endurance in the order of 20 minutes. The technical key parameters for the airframe are summarized in Table 1.

The FunJet airframe is quite robust and rather inexpensive (appr. 60 Euro). Its light weight and the corresponding low speed during landing minimize the risk of structural damage. Small fractures of fuselage or wings can easily be repaired by instant glue and activator spray within seconds. In case of a serious crash, the EPP material efficiently absorbs energy and prevents or at least reduces damage to the more valuable electronic components and sensors.

2.2 Autopilot system

For autonomous flight capability of SUMO the open-source autopilot system Paparazzi has been adapted. The system provides a flexible hard- and software structure for inexpensive autonomous aircraft operation. It basically consists of:

- the airborne processor board with sensors for the determination of the aircraft's attitude (GPS for position and speed and a set of 6 infrared sensors for the horizontal alignment)
- the airborne autopilot software
- the ground control station
- the online communication hardware and corresponding communication protocols
- a safety link option realized by a standard remote control (RC) transmitter system

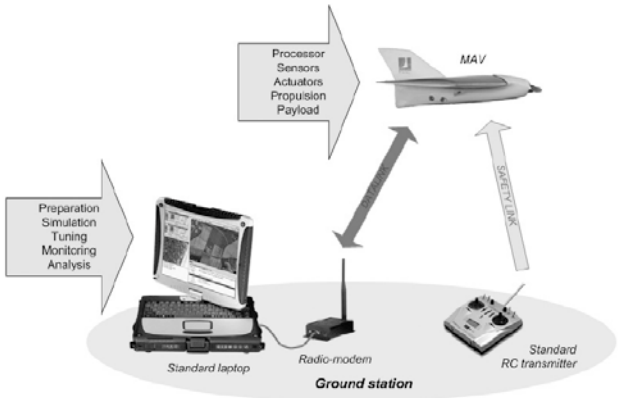

Figure 2: The main components of the SUMO system based on the Paparazzi autopilot solution.

Figure 2 gives a schematic overview of the main components of the system. A comprehensive description of the Paparazzi system and the basic principles of operation can be found in ENAC (2008) and BRISSET et al. (2006). As Paparazzi is an open source project, source code, hardware schematics and thorough documentation are released under the GNU Public License and freely available for anyone to download from the project website (http://paparazzi.enac.fr).

A powerful flight plan language allows the operator to define complex autonomous missions. The ground station operator can also manually navigate the aircraft at any time using video (currently not installed on SUMO), real-time GPS data, and/or visual contact while relying on the autopilot to perform only the flight stabilization. The ground control station also utilizes a powerful and flexible client/server architecture which allows the operator to control one or more aircrafts from a single location or from multiple locations.

The Paparazzi autopilot system has been specifically designed to be easily adaptable to any type of airframe and is currently used in various fixed and rotary wing systems. If required, the current additional payload capacity of the SUMO system of around 100 g could be easily extended by the choice of a larger airframe.

2.3 Meteorological sensors

SUMO is equipped with sensors for the measurement of pressure, temperature and relative humidity. The pressure sensor is mounted inside the fuselage, while the sensors for temperature and humidity are attached to the fuselage under the wings to provide good ventilation and to minimize radiation errors due to solar heating. Pressure is measured by the miniaturized (diameter 6.1 mm, height 1.7 mm) SCP1000 Absolute Pressure Sensor from VTI Technologies. Its measurement range covers 300 to 1200 hPa with a resolution of 0.015 hPa and an absolute pressure accuracy of 1.5 hPa in the range 600–1200 hPa. The relative pressure accuracy relevant for atmospheric profiling is 0.5 hPa. The pressure sensor is equipped with an onboard temperature sensor that provides in-flight temperature inside the aircraft, an important information for the estimation of battery capacity under cold environmental conditions.

Temperature and humidity are measured by the combined sensor SHT75 by Sensirion. The sensor element has a temperature range between –40 and 124°C and a resolution of 0.01 K. The absolute and relative accuracies are given as ± 0.5 K respectively ± 0.1 K. The humidity sensor covers 0–100% relative humidity with an absolute accuracy of ± 1.8 % and a reproducibility of ± 0.2 %. The ± 0.5 K accuracy is valid for the temperature range between 0 and 45°C and increases to ± 0.7 K at –20°C. The humidity sensor is temperature compensated. The given accuracy is expected to be independent of temperature and valid for the humidity range 10 to 90 %.

2.4 SUMO operation

In its current version and under actual legal aspects the SUMO system requires two persons for operation. The first one is preparing and controlling the autonomous mission on the ground control station (GCS), while the second is operating the standard remote control (RC) transmitter and acting as safety pilot during the flight. Take-off and landing are usually performed in manual mode, even though autonomous start is unproblematic and autonomous landing possible at least in flat terrain without obstacles. Further details on the practical aspects of SUMO operation can be found in REUDER et al. (2008) and JONASSEN (2008).

Figure 3 shows an example of the helical flight pattern used for boundary layer profiling. Typical ascent and descent rates of the SUMO aircraft are in the order of 7–10 m s^{-1}. The x and y values show the relative distance of SUMO to the launch site. The maximum height of this flight, performed during the FLOHOF campaign on Iceland (18.08.2007 17:56 UTC) was 2567 m, the overall flight duration 16 minutes.

Figure 4 visualizes the principle of wind determination of the SUMO system. It shows the instant ground speed from the on-board GPS for the descending part of the spiral. In one section, the ground speed is decelerated by headwind, indicated by blueish and greenish colors, while it is accelerated by tailwind in the opposite section of the spiral. Assuming constant true air speed, these ground speed differences can be used to calculate the horizontal wind speed and direction. Wind speed can be determined from the difference between minimum and maximum ground speed over a full circle, the corresponding wind direction from the position of minimum and maximum along the track. The assumption of constant true air speed is fulfilled in good approximation when operating the aircraft with constant throttle (zero during descent) and constant pitch angle. Even if there will be short-term deviations from this ideal state due to atmospheric turbulence, the assumption will hold as average over one full circle in the helical flight pattern. The determined wind profiles have of course to be seen as averages over such a full circle, which is for the typical used ascent and descent rates in between 200 m and

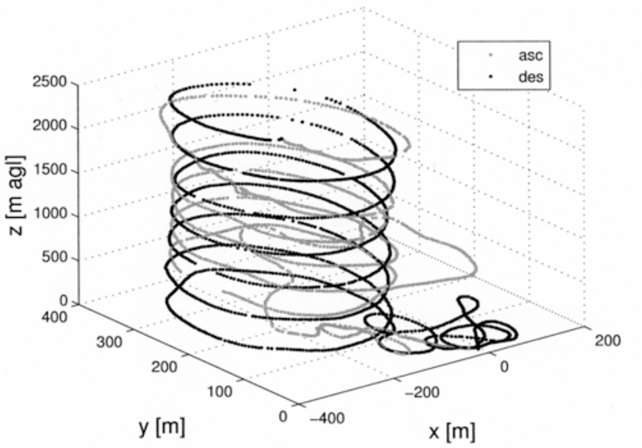

Figure 3: Typical flight pattern for atmospheric profiling. The ascent was performed during the FLOHOF campaign on Iceland, 18.08.2007, start time 17:56 UTC.

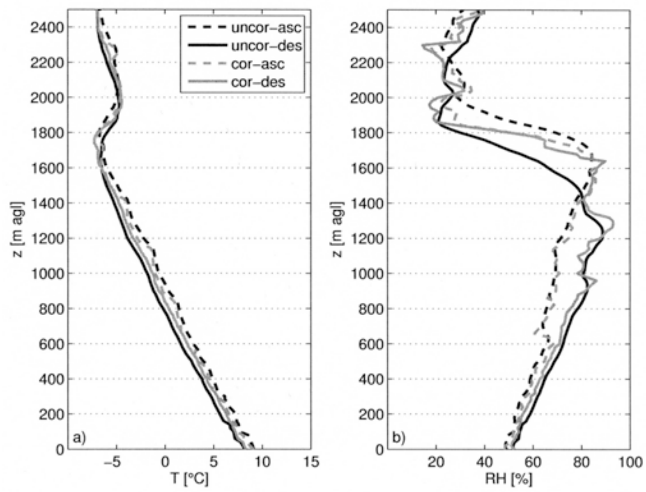

Figure 5: Example profiles for sensor time lag induced errors and their correction by a numeric filter algorithm. The measurements are taken during the FLOHOF campaign, 18.08.2007, 17:56 UTC.

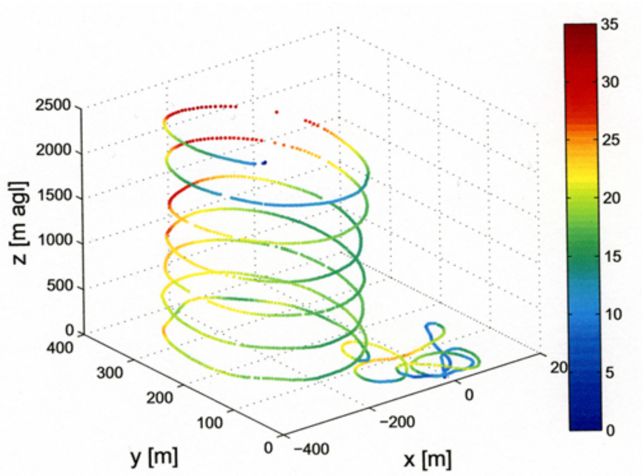

Figure 4: Descent data of Figure 3. The color indicates the ground speed of the aircraft in m s^{-1}.

500 m. It also has to be mentioned that the system cannot provide wind data in the manual mode usually used for SUMO operation below 150 m and for the circle at top ceiling, where throttle and pitch angle change from ascent to descent.

3 SUMO measurements

SUMO has been operated and tested during a total of four measurement campaigns. The first one, FLOHOF (FLOw over and around HOFsjökull) took place in July/August 2007 in Central Iceland and was mainly dedicated to the investigation of non-stationary gravity waves (for details see www.flohof.uib.no). Several ascents of the FLOHOF campaign on Iceland reached altitudes of more than 3000 m above ground. During a three week campaign on and around Spitsbergen in February/March 2008 the system has been operated for the first time in polar environment to investigate the Arctic ABL. Measurement flights have been performed from land near Longyearbyen, from sea ice, and from deck of the ice-breaking Norwegian coast guard vessel KV Svalbard. At surface temperatures around –20° C and boundary layer wind speeds of 10–15 m s^{-1} maximum altitudes of above 1500 m could be reached there. The last two field operations of SUMO have recently been performed in Germany. Up to now a total number of more than 150 meteorological measurement flights have been performed with two different SUMO airframes. The following section will exemplary present some of these measurements.

3.1 Sensor time lag correction

Due to the rather high ascent velocities of SUMO, time lag induced errors are a concern with respect to the interpretation of temperature and humidity profile measurements. Figure 5 shows temperature and humidity profiles taken on 18.08.2007, 17:56 UTC during the FLOHOF campaign. The black lines indicate the uncorrected raw data. It can be seen that the vertical structure of the associated parameters is well resolved. The most prominent feature is a marked inversion ranging from appr. 1800 to 2000 m, indicated by an increase in temperature of about 3 K and a corresponding decrease in humidity from above 80 % down to 20 %. A closer look on the uncorrected profiles reveals deviations between ascent and descent. At a given altitude they are in the order of 1.5 K for temperature and 5–10 % for relative humidity, which in this case corresponds to a vertical displacement of around 200 m, especially evident in humidity around the inversion. This feature has to be attributed to the sensor response time, leading to a general warm bias in the ascent and cold bias in descent. Correspondingly, the humidity has a dry bias during ascent and a wet bias during descent. Due to its deterministic nature, this error can be compensated for to a large extent by the application of a numerical correction scheme. The method used is based on the assumption that the change in sensor output with time is proportional to the difference between the instantaneous measured parameter value and the true ambient parameter value. The general solution of the corresponding differential equation can be approximated by a digital recursive filter equation. The critical parameter in this equation is the sensor time constant. By assuming that the state of the atmosphere remains nearly unchanged during the time interval between ascent and descent, the correction equation can be performed for a wide range of time constants. The final effective sensor time constant can be determined for each profile by minimizing the root mean square deviation between ascent and descent profiles. The detailed algorithm and its application to the SUMO data can be found in JONASSEN (2008). The corrected profiles are plotted in gray in Figure 5. A main indication of the scheme's effectiveness can be seen by both its ability to bring the profiles closer together and by positioning the inversion heights for relative humidity and temperature to the same level. The remaining deviation in relative humidity has not necessarily to be addressed to sensor problems (e.g. hysteresis). Humidity profiles during the whole FLOHOF campaign, taken by the remotely controlled aircraft KALI and by a tethered balloon, have documented the large spatial and temporal variability of relative humidity in the region.

3.2 Comparison with Vaisala radiosonde

During a research cruise with the Norwegian Coast Guard vessel KV Svalbard end of February 2008 the SUMO system was operated for the first time in an Arctic environment. Start and landing have been performed from the helicopter deck of the icebreaker. On February 28, SUMO has been launched nearly simultaneously with a Vaisala RS92 radiosonde operated by the Norwegian Navy, providing an excellent opportunity for a validation of the SUMO system by a well established and acknowledged atmospheric profiling system. The results of the comparison are presented in Figure 6. All profiles of the two independent systems show in general a very good agreement. The deviations in temperature are less than 0.5 K from ground level up to 1000 m, the SUMO ceiling height of this ascent. The profiles of relative humidity, wind speed and wind direction show somewhat larger differences. Nevertheless the basic structures of the profiles are captured satisfactory. As the radiosonde is drifting with the wind while SUMO is ascending stationary, the horizontal distance between both systems is increasing with height. Natural inhomogeneities especially of the humidity field in the marginal ice zone can easily explain the observed differences.

3.3 Case study 1: Development of the stable nocturnal boundary layer

In connection with the field course on soaring flight meteorology organized by the Meteorological Institute,

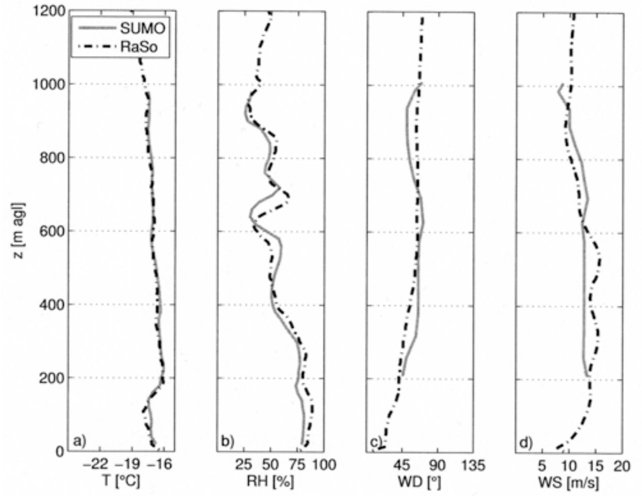

Figure 6: Meteorological profiles taken from the helicopter deck of the Norwegian Coast Guard vessel KV Svalbard at 76.74°N and 18.25°E in the marginal ice zone on 28.02.2008. (Take-off SUMO: 15:11; launch of radiosonde: 15:15 UTC)

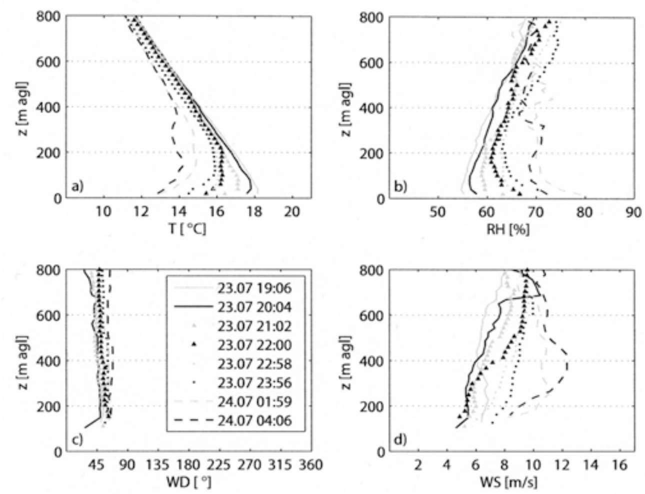

Figure 7: Example for the development of a stable nocturnal boundary layer. Airfield Coburg Steinrücken, 50.23°N and 10.99°E, 23./24.07.2008.

University of Munich, SUMO has been operated at the airfield Coburg Steinrücken. During fair weather conditions on July 23 and 24 an intense operation period has been conducted with amongst others hourly SUMO profile measurements. Figure 7 presents a subset of the data documenting the development of a stable nocturnal boundary layer during the clear night. The data set demonstrates the strength of the SUMO system, to provide high resolution boundary layer measurements with only marginal infrastructural requirements, i.e. battery power for the aircraft and the ground control laptop.

3.4 Case study 2: Horizontal variability

In August 2008 SUMO was operated as part of the Fluxpat experiment (http://www.meteo.uni-bonn.de/projekte

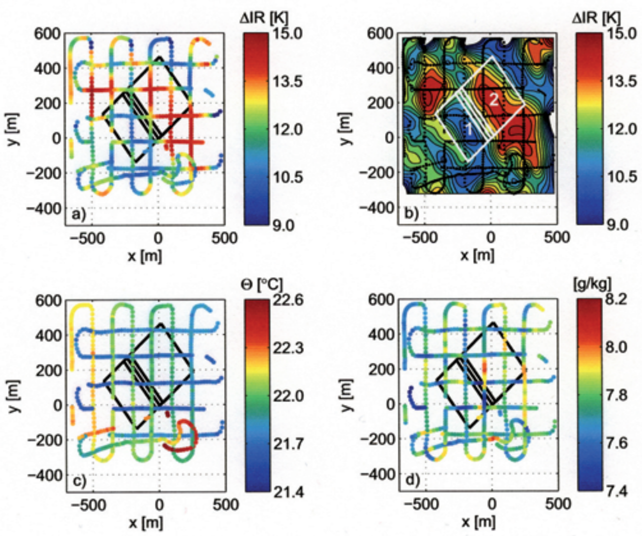

Figure 8: Results of a horizontal survey flight at about 100 m altitude during the Fluxpat experiment, 17.08.2008 10:55–11:11 UTC, 50.88 °N and 6.45 °E . The upper panels show the difference in IR radiation temperature between sky and ground ((a) raw data, (b) derived isoline plot). The lower panels present the patterns of potential temperature (c) and specific humidity (d). The black (white in (b)) boxes indicate the boundaries of fields with different agricultural use (1=sugar beet; 2=harvested wheat) instrumented with advanced micrometeorological measurement systems.

/tr32-wiki/doku.php/field_measurements) close to Jülich in Western Germany. The main motivation of SUMO operation during this campaign was to provide a link between ground based measurements and the flight data of the METAIR Dimona research aircraft and to monitor the horizontal variability of temperature and humidity fields over different types of agricultural land use. Therefore SUMO was mainly used for horizontal survey flights in altitudes of about 100 m. Figure 8 shows first results of one survey flight on August 17, 10:55-11:11 UTC under fair weather conditions with rather homogeneous altocumulus cloud cover and a wind speed of around 5 m s^{-1} from Southwest. First part of the flight was the East-West survey, followed by the North-South oriented survey afterwards, i.e. the measurements of the meteorological parameters at the crossing points of the survey grids can have time differences up to 15 minutes. Depicted are only measurement points where the aircraft operated in the altitude interval between 96 m and 116 m. Due to the homogeneous cloud, conditions the vertical oriented IR sensors of a 6 sensor array that is used for horizontal flight attitude stabilization, can also be used to get information on the surface temperature in terms of surface temperature differences. This information is visualized in the upper panels of Figure 8 as raw data along the flight path (a) and as interpolated continuous field (b). The picture clearly reveals a distinct surface temperature difference of 3–5 K between the vegetated sugar beet culture (denoted by 1 in panel (b)) and the vegetationless harvested wheat field (denoted by 2 in panel (b)).

A clear signature of the ground conditions can be found neither in temperature, nor in the humidity measurements. That is not really surprising at an altitude of around 100 m over ground in rather small scale and complex land-use areas. Nevertheless this first SUMO survey flights provide valuable additional meteorological information. For temperature it can be seen that there is a noticeable increase in temperature with time during the flight in the order of 0.5–1 K. The East-West surveys in the beginning of the flight reveal an average potential temperature of around 21.5°C, while nearly all values of the North-South survey exceed 22°C. A more detailed analysis of the flight pattern with respect to time can potentially help to estimate and understand the effects of advection in the actual measurement situation. The humidity measurements indicate a distinctly higher variability compared to temperature.

4 Summary and outlook

The SUMO system has proven its applicability for a wide range of in-situ ABL research applications, even under polar conditions. Comparisons with radiosondes and tethered balloon systems have shown that the meteorological profiles can be determined by SUMO in an accuracy comparable to well-established measurement systems. The most important advantage of the SUMO system is its easy-to-hand and cost-efficient performance requiring only minimal infrastructure. The material costs for one airborne SUMO unit, including the airframe with propulsion, the autopilot system and the meteorological sensors are in the order of 1200 Euro. This makes SUMO a valuable complementary boundary layer measurement system to radiosonde systems or atmospheric profilers on the basis of SODAR, RADAR or LIDAR.

SUMO is a project under constant development. At the moment, the operation of SUMO requires a distinct radiation temperature difference between sky and ground in the order of 10 K to stabilize its horizontal flight attitude. This limits the operation in clouds and under low clouds. In the future a combination of gyro and accelerometers could overcome this limitation. If a sufficient radiation temperature difference exists, the system can be operated during day and night, as proven in the presented measurements on the development of the nocturnal boundary layer in Figure 7. The implementation of a small dynamic pressure probe that would enable the verification of the constant true air speed assumption for the wind algorithm, is also desirable for the future. Measurement uncertainties related to sensor time-lag can potentially be minimized by the integration of faster sensors for temperature and humidity.

The results of the horizontal survey flights during Fluxpat indicate the requirement of safe autonomous SUMO operation closer to the ground. Suitable distance sensors on the basis of infrared radiation or small laser altimeters are under consideration as additional SUMO sensors. The integration of such sensors will also be one important step toward fully autonomous landing of the system. As the Paparazzi autopilot system can operate multiple SUMO units simultaneously, one of the boundary layer measurement strategies in the future will be the operation of SUMO in swarms or flocks. This will enable in-situ boundary layer measurements with unique spatial and temporal resolution. The availability of corresponding data sets will be crucial for the validation of fine scale numerical simulations and the test and improvement of the underlying boundary layer parameterization schemes and thus for future progress both in numerical weather prediction and in climate modeling.

The current legal situation for the operation of UAS is somewhat unclear, performing scientific measurements therefore often means operating in a gray area. In general UAS systems below 150 kg are subject to the national Civil Aviation Authorities. Corresponding applications for flight permission have to be addressed to them. The SUMO aircraft with its 580 g falls into the class of UAS below 7 kg. At the moment permissions are usually given for limited time periods and predefined areas. The application procedure and the applicable regulations are strongly varying from country to country. The development of internationally standardized methods for the application and approval of flight permissions for scientific purposes is therefore a key issue for further development of scientific UAV operations.

Acknowledgments

The authors are grateful to Christian LINDENBERG for his work on the assembly and maintenance of the airplanes and for his assistance as safety pilot during the flights on Iceland and Germany and to Michael KISLAT acting as safety pilot during the campaign on and around Spitsbergen.

The main financial support for development of SUMO was provided by the Meltzer University Foundation, Bergen, Norway. The comprehensive test of the system on Iceland in August 2007 would not have been possible without the FLOHOF field campaign funded by the German Research Foundation under contract EG 40/25-1. The arctic flights on and around Spitsbergen have been funded by the Norwegian Research Concil through its International Polar Year programme and the project IPY-THORPEX (grant number 175992/S30; www.ipy-thorpex.no) and a personal stipend of Marius JONASSEN (grant number 2008-356) provided by the Norwegian Polar Institute. Many thanks to the crew of the Norwegian Coast Guard vessel KV Svalbard for assistance during the research cruise.

The horizontal survey flights presented in this paper have been performed during late summer 2008 in the framework of the Fluxpat experiment as part of the Transregional Collaborative Research Centre 32 [Transregio/ SFB32] supported by the German Science Foundation (DFG) under grants TR32.

References

BRISSET, P., A. DROUIN, M. GORRAZ, P.-S. HUARD, J. TYLER, 2006: The Paparazzi solution. http://www.recherche.enac.fr/paparazzi/papers_2006/mav06_paparazzi.pdf.

EGGER, J., S. BAJRACHAYA, R. HEINRICH, P. KOLB, S. LAEMMLEIN, M. MECH, J. REUDER, W. SCHAEPER, P. SHAKYA, H. WENDT, 2002: Diurnal winds in the Himalayan Kali Gandaki valley. Part III: Remotely piloted aircraft soundings. – Mon. Wea. Rev. **130**, 2042–2058.

EGGER, J., L. BLACUTT, F. GHEZZI, R. HEINRICH, P. KOLB, S. LAEMMLEIN, M. LEEB, S. MAYER, E. PALENQUE, J. REUDER, W. SCHAEPER, J. SCHWEEN, R. TORREZ, F. ZARATTI, 2005: Diurnal circulation of the Bolivian Altiplano. Part I: Observations. – Mon. Wea. Rev. **133**, 911–924.

ENAC, 2008: Paparazzi user's manual. – http://paparazzi.enac.fr/wiki_images/Users_manual.pdf

HOLLAND, G.J., P.J. WEBSTER, J.A. CURRY, G. TYRELL, D. GAUNTLETT, G. BRETT, J. BECKER, R. HOAG, W. VAGLIENTI, 2001: The Aerosonde robotic aircraft: A new paradigm for environmental observations. – BAMS **82**, 889.

JONASSEN, M., 2008: The small unmanned meteorological observer (SUMO): Characterization and test of a new measurement system for atmospheric boundary layer research. – Master thesis, Geophysical Institute, University of Bergen, Norway

KONRAD, T.G., M.L. HILL, J. R. ROWLAND, J.H. MEYER, 1970: A small, radio-controlled aircraft as a platform for meteorological sensors. – Appl. Phys. Lab. Tech. Digest 11.

MA, S., H. CHEN, G. WANG, Y. PAN, Q. LI, 2004: A miniature robotic plane meteorological sounding system. – Adv. Atmos. Sci. **21**, 890.

MAHESH, A., V.P. WALDEN, S.G. WARREN, 1997: Radiosonde temperature measurements in strong inversions: Correction for thermal lag based on an experiment at the south pole. – J. Atmos. Ocean. Tech. **14**, 45–53.

MILOSHEVICH, L.M., A. PAUKKUNEN, H. VOEMEL, S. J. OLTMANS, 2004: Development and validation of a time-lag correction for vaisala radiosonde humidity measurements. – J. Atmos. Ocean. Tech. **21**, 1305–1327.

REUDER, J., B. BRISSET, M. JONASSEN, M. MUELLER, S. MAYER, 2008: Sumo: A small unmanned meteorological observer for atmospheric boundary layer research. – Earth and Environmental Science **1**, doi:10.1088/1755–1307/1/1/012014, 10pp.

SPIESS, T., J. BANGE, M. BUSCHMANN, P. VOERSMANN, 2007: First application of the meteorological Mini-UAV 'M2AV'. – Meteorol. Z. **16**, 159.

STENSRUD, D.J., 2007: Parameterization Schemes: Keys to Understanding Numerical Weather Prediction Models – Cambridge University Press.

STULL, R.B., 1997: An Introduction to Boundary Layer Meteorology – Kluwer Academic Publishing, Dordrecht, The Netherlands.