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SUMO: A SMALL UNMANNED METEOROLOGICAL OBSERVER FOR ATMOSPHERIC BOUNDARY LAYER RESEARCH

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1. INTRODUCTION

The key for the understanding of exchange processes in the Atmospheric Boundary Layer (ABL) is the detailed information on the vertical structure and the horizontal variability of the lower atmosphere, especially with respect to temperature, humidity and wind. Further improvement of this understanding requires novel approaches by combining fine-scale modeling efforts and innovative measurement strategies retrieving data of appropriate spatial and temporal resolution. Corresponding work is crucial for the validation and the further improvement of boundary layer parameterization schemes and thus for future progress both in numerical weather prediction and in climate modeling. Up to now there is a lack of cost efficient measurement systems, applicable for ABL phenomena covering horizontal scales between 100 m up to a few kilometers.

2. THE SUMO SYSTEM

The Small Unmanned Meteorological Observer (SUMO) has been developed as a mobile and cost-efficient platform for the determination of the vertical distribution of temperature, humidity, wind speed and wind direction in the ABL and can be operated as "recoverable radiosonde" for boundary layer research. In its recent version, it is based on a commercially available model plane construction kit equipped with an 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 (GCS) during SUMO operation.

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Figure 1: *SUMO airframe based on the model construction kit FunJet by Multiplex and the Panasonic CF-19 Toughbook used as ground control station.*

2.1. Airframe

The construction kit FunJet manufactured by Multiplex is used as airframe of the presented prototype of SUMO. It is a delta-wing pusher prop jet composed of lightweight foam material EPP (expanded polypropylen), electrically powered by a brushless motor (AXI 2212/26) driving a 9"x 6" propeller. A lithium polymer (LiPo) battery pack with a capacity of 2100 mAh enables a flight endurance of around 20-30 minutes. Due to its size and weight, the SUMO system is highly mobile and easy to operate, even in remote areas and under harsh environmental conditions. The technical details are summarized in table 1.

The FunJet airframe is quite robust and rather inexpensive (below 100 Euro). Its light weight and the corresponding low speed during landing minimizes the risk of structural damage. Additionally, EPP can be repaired by instant glue and activator spray within seconds if fractures of the fuselage or wings should occur.

Table 1: *Technical details of the FunJet airframe used as platform for the SUMO system*

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

2.2. ***The Paparazzi autopilot project***

For autonomous navigation, SUMO uses the open source Paparazzi autopilot system (Brisset et al., 2006). The corresponding project was founded in 2003 by a team of enthusiastic individuals with the aim to enable inexpensive autonomous UAV operation. Since its start, the project has enjoyed constant growth and is now, in addition to its use by several individual teams around the world, officially being developed at Ecole Nationale de l'Aviation Civile (ENAC), the French National School of Civil Aviation.

Paparazzi is an open source autopilot system oriented toward inexpensive autonomous aircraft operation. The system has been designed to be easily adapted to any type of airframe and is currently used in both fixed and rotary wing systems. It basically consists of:

- the airborne processor board with its required sensors for the determination of the aircrafts attitude (mainly GPS for position and speed and a set of infrared sensors for the horizontal alignment)
- the airborne autopilot software
- the ground control station
- the online communication hardware and communication protocols
- a standard remote control (RC) transmitter as safety link option

The main components of the system are schematically depicted in Figure 2. A comprehensive overview of hard- and software setup and configuration as well as the basic principles of operation of the Paparazzi solution can be found in Brisset et al. (2006) and ENAC (2008).

A powerful flight plan language allows the operator to define complex autonomous missions and create a logical tree of autonomous decisions for the system to make while in flight to perform any task or adapt to any scenario. The ground station operator can also manually navigate the aircraft at any time using video (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 utilizes a powerful and flexible client/server architecture which allows the operator to control one or more aircraft from a single location or from multiple locations.

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 heating by solar radiation. 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 especially under cold environmental conditions. Temperature and humidity is measured by the sensor DigiPicco I2C manufactured by IST. It combines a PT1000 temperature element with the capacitive humidity sensor P14 SMD. During operation it turned out that the temperature sensor shows a distinctly slower response than the humidity sensor, most likely due to its location on the circuit board behind the humidity sensor. Therefore a second, independent and faster sensor combination (SHT75 by Sensirion) has been additionally mounted in autumn 2007 for the latest measurements.

2.4. ***Operation of SUMO for atmospheric profiling***

In general the SUMO system requires two persons for operation. One is preparing and controlling the autonomous mission on the ground control station (GCS), while the other 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 generally unproblematic and autonomous landing is possible at least in flat terrain and under weak wind conditions.

The following favorable mode of operation has been developed during numerous meteorological ascents. SUMO is started manually and flown to a safe altitude of around 100 m above ground. Then the pilot switches control from the RC transmitter to the GCS for autonomous flight. The aircraft is first sent in a standby mode, i.e. flying circles around a defined home point at a given altitude of 150 m. This enables a check of proper aircraft functionality and allows for the adjustment of the temperature and humidity sensors to the environmental conditions. The next step of the flight plan is an upward profile to a user-defined altitude that can be changed in-flight. For that purpose, the airplane is operated with constant throttle and constant pitch angle, the autopilot uses variations of the roll angle to keep the aircraft on its circular upward spiraling track. After reaching the defined maximum altitude, the engine is switched off and the pitch angle set to a constant negative value. From that point the aircraft is gliding down on a spiral track until reaching the safety altitude of 150 m. From there, the pilot is taking control for manual landing. Figure 2 shows an example of a typical helical flight pattern for boundary layer profiling, where different colors are used for ascent and descent. 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 with respect to height above ground. The maximum height of this flight was 2567 m at an overall flight duration of 16 minutes. Especially at higher altitudes there are some data gaps in the track due to loss of telemetry connection for a few seconds.

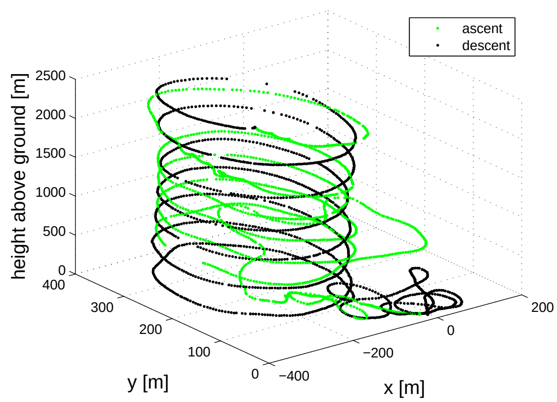

Figure 2: *Typical SUMO flight pattern for atmospheric profiling. The color indicates ascent and descent. The ascent was performed during the FLOHOF campaign on Central Iceland, 18.08.2007, 17:56 UTC. It reached an maximum altitude of more than 2500 m above ground after 8 minutes of flight. Overall flight time was 16 minutes in this example.*

Figure 3 shows the instant ground speed from on-board GPS at each position of the track by color code. 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, indicated by yellowish and reddish colors. Assuming constant true air speed, these ground speed differences can be used to determine the horizontal wind speed and direction. Operating the aircraft with constant throttle (zero during descent) and constant pitch angle, this assumption is fulfilled in good approximation. 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.

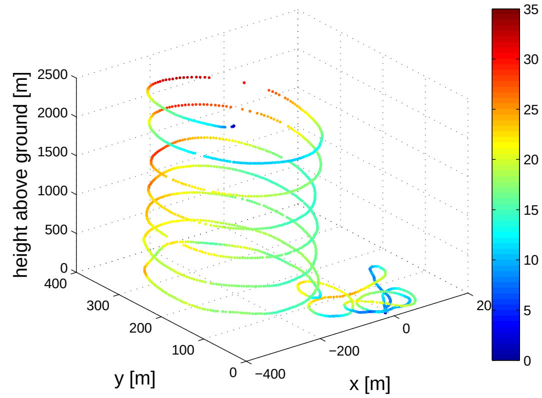

Figure 3: *Descent data of Figure 2. The color code indicates the ground speed from GPS measurements im m s^{-1}.*

3. MEASUREMENTS

SUMO has been extensively tested during two measurement campaigns. The first one, FLOHOF (FLOw over and around HOFsjokull) 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). During a 3 week campaign on and around Spitsbergen in February/March 2008 the system has been operated for the first time in polar environment to investigate its performance for arctic ABL measurements. SUMO flights have been performed from land near Longyearbyen, from sea ice, and from deck of the ice-breaking Norwegian coast guard vessel KV Svalbard.

During both campaigns a total number of more than 70 meteorological profiling ascents have been performed with one airframe. Several ascents of the FLOHOF campaign on Iceland reached altitudes of above 3000 m. Under arctic conditions on and around Spitsbergen, with surface temperatures around -20 ^{o}C and boundary layer wind speeds of 10-15 m s^{-1} maximum altitudes of above 1500 m could be reached.

3.1. Sensor time-lag correction

The energy optimized operation of SUMO for high altitude soundings requires quite large ascent and descent velocities in the order of 7-10 m s^{-1}. Due to sensor time-lag this induces a typical warm (dry) bias during ascent and a corresponding cold (moist) bias during descent (dotted lines in Figure 4). A corresponding correction method based on numerical digital filtering has been developed and tested (Jonassen, 2008). The resulting improvement by this method can also be seen in Figure 4 (solid lines). The absolute values of temperature and humidity are closely gathered and the location of the inversion is placed at a definite level.

explained by the spatial difference of SUMO and radiosonde measurements in the marginal ice zone, where large variability in humidity can be expected. The comparison between the time-lag corrected (red) and uncorrected (blue) humidity data indicates the efficiency of the applied correction scheme.

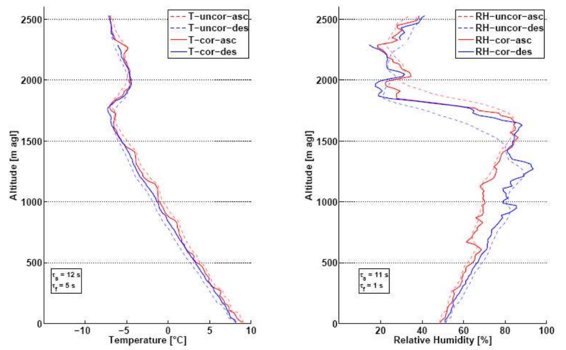

Figure 4: *Exemplary result of the sensor time-lag correction scheme used for the SUMO measurements.*

3.1. Intercomparison with a radiosonde ascent

The measurements of this intercomparison were performed in the marginal ice zone during a scientific cruise with the Norwegian Coast Guard vessel KV Svalbard, late February 2008. During this cruise, several radiosondes were launched in connection to the International Polar Year campaign IPY-THORPEX. One of these radiosondes was exactly timed with the operation of SUMO.

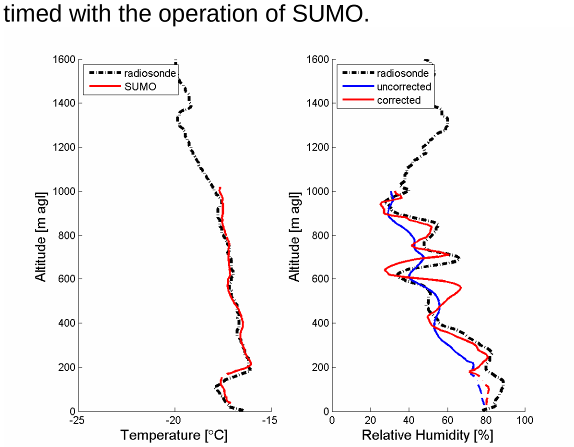

Figure 5: *Comparison of SUMO profiles of temperature and humidity with a radiosounding, performed on 28.02.2008 in the marginal ice zone in Storfjorden, East of the main island of Spitsbergen (76.74 ^{o}N, 18.25 ^{o}E). Start SUMO: 15:11 UTC, launch radiosonde: 15:15 UTC.*

The results of this intercomparison are presented in Figure 5 for temperature and humidity and Figure 6 for wind speed and wind direction. The temperature profiles show an excellent agreement of better than ± 0.5 K from the ground up to around 1000 m, the maximum altitude reached by SUMO during this ascent. For humidity, the deviations between both systems are somewhat larger. Nevertheless, the main structure of the time-lag corrected SUMO profile fits reasonably with the corresponding radiosonde data. The remaining deviations can at least partially be

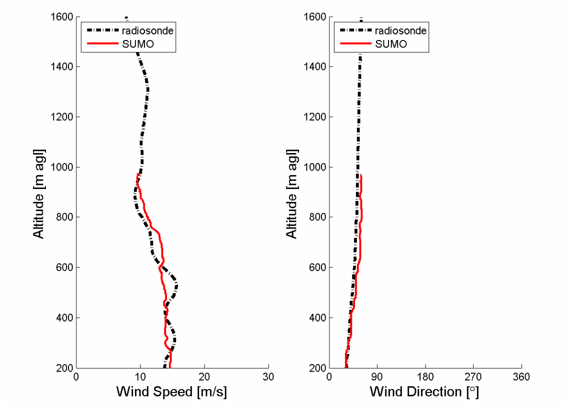

Figure 5: *Comparison of SUMO profiles of wind speed and wind direction with a radiosounding, performed on 28.02.2008 in the marginal ice zone in Storfjorden, East of the main island of Spitsbergen (76.74 ^{o}N, 18.25 ^{o}E). Start SUMO: 15:11 UTC, launch radiosonde: 15:15 UTC.*

In general the wind profiles of both systems also show a very good agreement. However the radiosounding provides more structure in the vertical wind speed field. The reason for this is the averaging over one circle in the SUMO wind algorithm that corresponds to a layer of typically 300-400 m.

4. SUMMARY AND OUTLOOK

The most important advantage of the SUMO system is its easy-to-hand and cost-efficient performance. During the Spitsbergen campaign, the ground control station was for the first time operated exclusively by scientists rather than aircraft specialists. This proves that the Paparazzi system has now reached a level of user-friendliness that enables operation after rather short training.

The new sensors for temperature and humidity provide the corresponding profiles in an accuracy comparable to that of the latest and well-established radiosonde systems.

By keeping strictly to the circling/helical flight pattern, no additional equipment is needed to determine wind profiles. The method uses only modules which are part of the autopilot system anyway. It has to be stressed that the wind estimation method works only for a circling/helical flight pattern which can only be precisely achieved in auto mode. First validations of the SUMO wind profiles indicate that this information can be obtained at least satisfactory.

Nevertheless the wind estimation method in use has further potential for improvements, thus one main focus in the future will be set on corresponding validation and intercomparison with the available parallel radiosonde ascents during the Spitsbergen campaign and by the performance of tailored validation campaigns, e.g. flying SUMO around high meteorological towers. In this context the ongoing Gufuskalar project, equipping a 412 m high mast in Northwest-Iceland with meteorological instrument-tation, will be of specific interest.

For safety reasons, the auto mode could not be used for heights closer than 150 m above ground during the field campaigns in 2007 and 2008. For the future it is desirable that additional circles in autonomous mode will be flown close to the ground. This will require additional SUMO sensors for continuous monitoring of the distance to the ground. The integration of such sensors will also be one important step toward fully autonomous landing.

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References

ENAC, 2008: The Paparazzi User Manual, http://paparazzi.enac.fr/wiki_images/Users_manual.pdf

Brisset, P., Drouin, A., Gorraz, M., Huard, P. and Tyler, J., 2006: The Paparazzi Solution, http://www.recherche.enac.fr/paparazzi/papers_2006/mav06_paparazzi.pdf.

Jonassen, M., 2008: The Small Unmanned Meteorological Observer (SUMO) – Characterization and test of a new measurement system for atmospheric boundary layer research. Master thesis, University of Bergen, Norway.