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

J. Reuder\textsuperscript{1}, P. Brisset\textsuperscript{2}, M. Jonassen\textsuperscript{1}, M. Müller\textsuperscript{3}, and S. Mayer\textsuperscript{1}

\textsuperscript{1} Geophysical Institute, University of Bergen, Allegaten 70, 5009 Bergen, Norway
\textsuperscript{2} Ecole Nationale de l’Aviation Civile (ENAC), 7 avenue Edouard Belin, 31055 Toulouse, France
\textsuperscript{3} Orleansstrasse 26a, 31135 Hildesheim, Germany

E-mail: joachim.reuder@gfi.uib.no
pascal.brisset@enac.fr
marius.jonassen@gfi.uib.no
martin@pfump.org
stephanie.mayer@gfi.uib.no

Abstract. A new system for atmospheric measurements in the lower troposphere has been developed and successfully tested. The presented Small Unmanned Meteorological Observer (SUMO) is based on a light-weighted commercially available model airplane, equipped with an autopilot and meteorological sensors for temperature, humidity and pressure. During the 5 week field campaign FLOHOF (Flow over and around Hofsjökull) in Central Iceland the system has been successfully tested in July/August 2007. Atmospheric profiles of temperature, humidity, wind speed and wind direction have been determined up to 3500 m above ground. In addition the applicability of SUMO for horizontal surveys up to 4 km away from the launch site has been approved. During a 3 week campaign on and around Spitsbergen in February/March 2008 the SUMO system also proved its functionality under harsh polar conditions, reaching altitudes above 1500 m at ground temperatures of -20°C and wind speeds up to 15 m s\textsuperscript{-1}.

With its wingspan of 80 cm, its length of 75 cm and its weight of below 600 g, SUMO is easy to transport and operate even in remote areas. The direct material costs for one SUMO unit, including airplane, autopilot and sensors are below 1200 Euro. Assuming at least several tenths of flights for each airframe, SUMO provides a cost-efficient measurement system with a large potential to close the existing observational gap of reasonable atmospheric measurement systems in between meteorological masts/towers and radiosondes.

1. Introduction

Detailed information on the vertical structure and the horizontal variability of the lower atmosphere, especially with respect to temperature, humidity and wind, is the key for the understanding of exchange processes in the Atmospheric Boundary Layer (ABL). Further improvement of this understanding requires a combination of fine-scale modeling efforts and innovative measurement strategies. Corresponding work is crucial for the validation and 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 10 km. First attempts on the basis of remotely controlled small unmanned aerial vehicles (SUAVs) have already been started some decades ago [1], and the systems have gradually been improved until today. A corresponding profiling system (KALI) has for example been developed at the University of Munich, Germany and has been successfully used during several field campaigns in Nepal, Bolivia and Germany to measure atmospheric profiles of pressure, temperature and humidity up to 3 km above ground (e.g. [2], [3]).

The two main shortcomings of that system are 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. In addition, smaller, faster and cheaper sensors for meteorological parameters and positioning purposes (e.g. GPS) are available now. Sporadic attempts to use and combine this new technical potential for atmospheric measurements have shown some promising results [4], [5], [6].

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 during SUMO operation.

![Figure 1. The SUMO airframe based on the model airplane FunJet by Multiplex and the laptop used as ground control unit.](image)

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 polypropylene), 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.

| Table 1. Technical details 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     |

The FunJet airframe is quite robust and rather inexpensive (below 100 Euro). Its light weight and the corresponding low speed during landing minimize 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.

2.2. Paparazzi autopilot system

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 [7] and [8] or on the corresponding home page of the Paparazzi project (http://paparazzi.enac.fr/wiki/index.php/Main_Page).

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.
As mentioned above, Paparazzi is an open source project. Source code, hardware schematics
and thorough documentation are released under the GNU Public License and are freely available
for anyone to download from the project website mentioned above.

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 capacitative 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. The main specifications of the temperature and humidity
sensors are summarized in table 2.

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.

Figure 2. The main components of the SUMO system based on the Paparazzi autopilot solution.
Table 2. Specifications of the temperature and humidity sensors used on.

<table>
<thead>
<tr>
<th>parameter</th>
<th>DigiPicco</th>
<th>SHT 75</th>
</tr>
</thead>
<tbody>
<tr>
<td>resolution RH</td>
<td>0.003 %</td>
<td>0.03 %</td>
</tr>
<tr>
<td>resolution T</td>
<td>0.005 K</td>
<td>0.01 K</td>
</tr>
<tr>
<td>range RH</td>
<td>0-100 %</td>
<td>0-100 %</td>
</tr>
<tr>
<td>range T</td>
<td>-40 - 50 °C</td>
<td>-40 - 124 °C</td>
</tr>
<tr>
<td>abs. Accuracy RH</td>
<td>&lt; 3 %</td>
<td>±1.8 %</td>
</tr>
<tr>
<td>abs. Accuracy T</td>
<td>±0.5 K</td>
<td>±0.5 K</td>
</tr>
<tr>
<td>rel. Accuracy RH</td>
<td>N/A</td>
<td>±0.1 %</td>
</tr>
<tr>
<td>rel. Accuracy T</td>
<td>N/A</td>
<td>±0.1 K</td>
</tr>
<tr>
<td>response time</td>
<td>5 s</td>
<td>6 s</td>
</tr>
</tbody>
</table>

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. Fig. 3 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 3. An example of a typical flight pattern during the FLOHOF campaign on Iceland. The ascent starts at 17:56 UTC on 18.08.2007.

Figure 4. As in fig. 3, but only descent. The colors indicate the ground speed of the aircraft given in m s\(^{-1}\).
Figure 4 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.

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 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. 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 °C and boundary layer wind speeds of 10-15 m s⁻¹ maximum altitudes of above 1500 m could be reached. The following section will exemplary present temperature, humidity and wind profiles, measured by the SUMO system.

![Figure 5](image_url)

**Figure 5.** Profiles of wind speed (a) and wind direction (b) measured during the FLOHOF campaign on 18.08.2007. SUMO started at 17:56 UTC, the PiBal ascent at 18:54 UTC.

![Figure 6](image_url)

**Figure 6.** Projection of the SUMO and PiBal tracks to the horizontal x-y plane for the intercomparison presented in figure 5.

3.1. Wind profiles
Figure 5 presents an example of the profiles of wind speed and wind direction derived by the method described above. In accordance with the corresponding temperature and humidity profiles, showing a distinct capping inversion (figure 7), the ascent represents a well developed
boundary layer with rather week and constant wind speed of 3-5 m s$^{-1}$ up to 1600 m above ground. The wind direction near the ground is W, slightly turning to the left with height. At the inversion the wind speed starts to increase to values above 10 m s$^{-1}$, while the wind direction changes to WNW.

The SUMO wind profile starts at 500 m above ground for the ascent (green) and ends at 150 m above ground in the descent (black). This is due to the fact that SUMO did not fly in autonomous mode below approximately 250 m. In order to obtain wind information via the optimization algorithm the first (last) circle in the auto mode flight pattern has to be completed in the ascent (descent). Therefore, the wind information has to be corrected with respect to height depending on the flight pattern’s helical stretching (not shown).

In order to validate the wind estimation method, SUMO ascents have been compared to Pilot Balloon (PiBal) ascents. This method uses small helium filled balloons that are released and optically tracked with two theodolites (e.g. [9]). The corresponding measurement data and their error estimates are plotted in figure 5 in blue. Compared to SUMO, the PiBal method shows very similar wind profiles - both in speed and direction - between 150 up to 1250 m above ground. The large error bars above about 1300 m in the PiBal ascent show the limitation of this system due to a strong increase in uncertainty with increasing distance of the balloon from the observer [10]. Taking into account the delay of about one hour between SUMO and PiBal ascent and the spatial offset due to the drift of the balloon with the wind (see figure 6), the correspondence between the two measurement methods is quite well and promising.

### 3.2 Temperature and humidity profiles

Figure 7 shows the temperature and humidity profiles taken at the same time as the wind measurements from FLOHOF discussed in the previous section. 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 25 %.

The ascent and descent profiles show systematic deviations at a given altitude that are in the

![Figure 7](image-url)
order of 1.5 K for temperature and 5-10 % for relative humidity. A closer look reveals that it can be mainly seen as a systematic height displacement, 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 profiles after application of such a scheme are plotted as dashed lines in figure 7. 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.

3.3. Measurements in the Arctic ABL

Figure 8 shows an example of temperature and humidity profiles obtained during the field campaign on and around Spitsbergen in late winter 2008. Here only the results from the descending part of profile are included, because it turned out that the ascent profiles were subject to a distinct warm bias in the lowest levels. This is caused by residual heat due to the large temperature differences between the laboratory for flight preparation (+15 °C) and the measurement environment itself (-20 °C ). A new feature of the SUMO system during this campaign was the inclusion of an additional, faster sensor for temperature and relative humidity. The results from both sensor sets are presented and compared in figure 8.

Figure 8. Profiles of temperature and relative humidity taken onboard 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)

In comparison to most profiles obtained at Iceland, the profiles from the Spitsbergen area, have generally signs of a more complex lower level structure often characterized by multiple
inversions. A central question is how well SUMO is able to resemble the true vertical structure of these fine scale features. The answer was sought through an intercomparison with a radiosonde (Vaisala RS92), which represents a well established and acknowledged measurement platform. SUMO (15:11 UTC) and the radiosonde (15:15) have been launched nearly simultaneously and the ascent rates of both systems are rather similar. It turns out that the temperature profiles of both SUMO sensors and the radiosonde are in excellent agreement of better than 0.5 K from 50 m to the maximum SUMO height of 1000 m during this ascent. The irregularity around 200 m altitude can be explained by a short term ascending motion of the aircraft after switching back from autopilot into manual mode. The relative humidity values have somewhat larger deviations, especially in comparison to the gradients, possibly indicating a generally longer response time for the SUMO instruments than for those of the radiosonde. Furthermore, the measurements from the newest sensor seem to reveal more details than for the old one, indicating a shorter time constant.

Wind profiles of the Spitsbergen campaign are not yet evaluated, but will also be compared to the radiosoundings soon.

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. First validations of the SUMO wind profiles indicate that this information can be obtained at least satisfactory. By keeping strictly to the circling/helical flight pattern, no additional equipment is needed to require information about the horizontal wind. 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. 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.

The wind estimation method in use has clearly 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 instrumentation, will be of large importance.

Acknowledgments

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