Determination of temperature and humidity profiles in the atmospheric boundary layer by fast ascending UAVs

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Introduction

Meteorological UAVs (unmanned aerial vehicles) represent an economical and flexible platform for measurements of temperature and humidity in the atmospheric boundary layer. A corresponding measurement system is under development at the University of Bergen. The system, SUMO (**S**mall **U**nmanned **M**eteorological **O**bserver), has proven its functionality during the field campaign FLOHOF in the central parts of Iceland (July/August 2007), and during the IPY-THORPEX campaign on and around Spitsbergen (February/March 2008).

Due to energy related issues (i.e. battery capacity), a compromise has to be done between ascent/descent speed and accuracy of the measurements when profiling the atmosphere with an ultra light UAV such as SUMO. The resulting energetically optimized ascent/descent speed is in the order of 7-10 m/s, a relative high speed compared to e.g. radiosondes which have a typical ascent speed of around 5 m/s. Since the temperature and humidity sensors need a certain time to adapt to their ambient environment the result of the high vertical speed is typically a warm bias in ascent and a cold bias in descent data. Measurements taken during FLOHOF show that the associated time lag of the sensors is of a rather deterministic nature and of a noticeable magnitude worth to be corrected. A numerical method based on digital filters is used for this purpose. The method is investigated and applied to temperature and humidity profiles measured during the Iceland and Spitsbergen campaigns. Examples of corrected profiles are presented and compared with the data of another established UAV system, KALI (e.g. Egger et al., 2002), and radiosoundings.

Field campaigns

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.

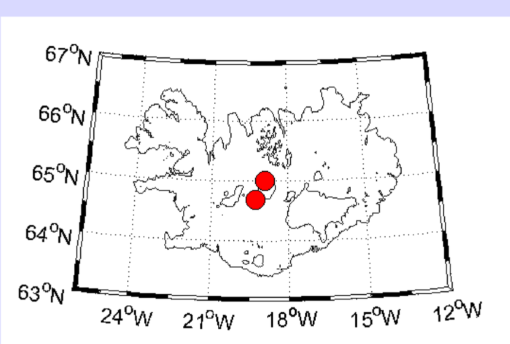

Figure 1: Location of the measurement sites during the FLOHOF campaign on Iceland in summer 2007. Both sites are located in the Icelandic highlands, near the Hofsjökull glacier.

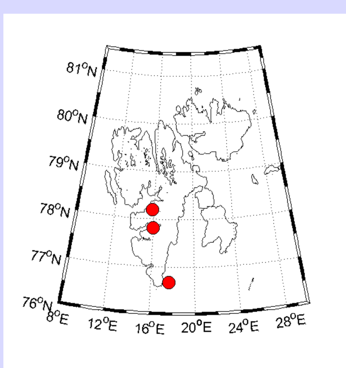

Figure 2: Location of SUMO measurements on and around Spitsbergen during the IPY-THORPEX campaign in late winter 2008: Storfjorden in the South, Van Mijenfjorden near Svea in the middle, and the northernmost location is in the vicinity of Longyearbyen.

The SUMO system

The SUMO system is based on a commercially available model airplane construction kit (FunJet from Mulitiplex) equipped with meteorological sensors for the measurement of temperature, humidity and pressure. For autonomous navigation, the SUMO system uses Paparazzi, an open source autopilot system. The pressure sensor (SCP1000 by VTI Technologies) is mounted inside the fuselage. The combined temperature humidity sensor (SHT75 by Sensirion in the recent SUMO version, DigiPicco I2C by IST during the FLOHOF campaign) is mounted at the side of the fuselage under the wings to minimize heating by insolation.

Figure 3: The SUMO aircraft and the laptop used as ground control station during operations.

SUMO is intended to provide a cost-efficient measurement and profiling system for atmospheric boundary layer research that can be operated as "recoverable radiosonde". The use of the FunJet construction kit (~150 €, including an advanced brushless motor) and the open source Paparazzi autopilot system (~500 € for required electronic boards and components and communication hardware) keeps the overall costs of the system very low. Of course working time for assembly, calibration, and test flights (about one week) are not included in this calculation.

Length	75 cm
Wingspan	80 cm
Weight	580 g
Average airspeed	12-18 m/s
Maximum airspeed	35 m/s
Average ascent rate	7-10 m/s
Maximum ascent rate	15 m/s
Maximum altitude above ground	3.5 km+
Endurance	Up to 30 min

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

The Paparazzi autopilot system is oriented toward inexpensive autonomous aircraft operation. It has been designed under lead-management of ENAC (Ecole Nationale de l'Aviation Civile), Toulouse, France to be easily adapted to any type of airframe and is currently used in both fixed and rotary wing systems.

The system provides a user-friendly ground control station with advanced flight plan management and inflight change option. Meteorological data and aircraft attitude are transmitted continuously with an update frequency of 4 Hz.

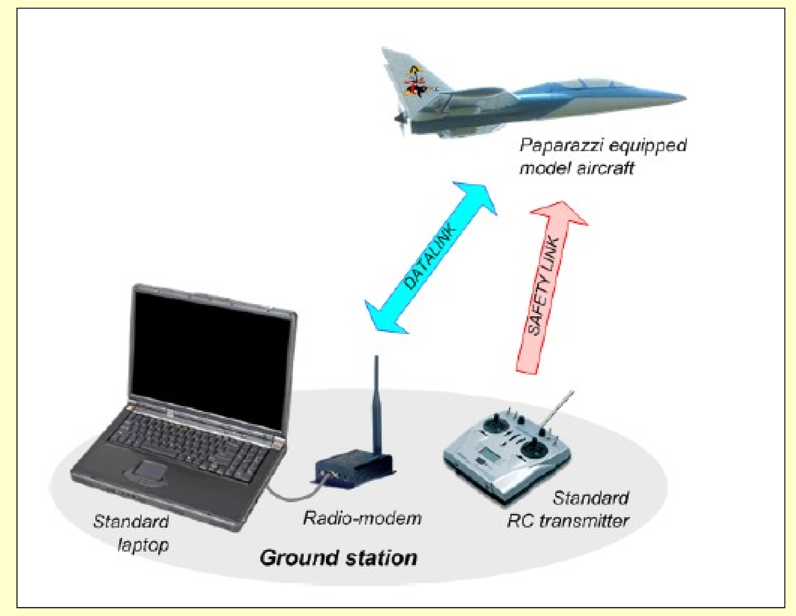

Figure 4: The Paparazzi system consists of the following four main components; An airborne part, a ground station, a radio modem and a safety remote control transmitter.

Time-lag correction of temperature and humidity profiles

A systematic bias in ascent and descent temperature and relative humidity data that results from a relative slow sensor response, is corrected for through the application of a numerical correction scheme based on digital filters. This is possible because the ambient information is contained in the sensor output signal, but appears as smoothed in time. The high ascent/descent rates of SUMO do not give the sensor time enough to adapt to its environment. The associated sensor response time (τ_s) can be derived from the difference between corresponding ascent and descent data from several soundings.

The described correction scheme is successfully applied to temperature and relative humidity data from both the FLOHOF and Spitsbergen campaign and show a significant improvement of the accuracy of the corresponding parameters (Figs. 5 and 8). For the FLOHOF data, the sensor response time (τ_s) were estimated to 12 and 11s for temperature and relative humidity, respectively. The corresponding constants for the smoothing filter (τ_f) were 5 and 1s. Lower temperatures under the Spitsbergen campaign caused an increase in the relative humidity sensor time constant to 30s.

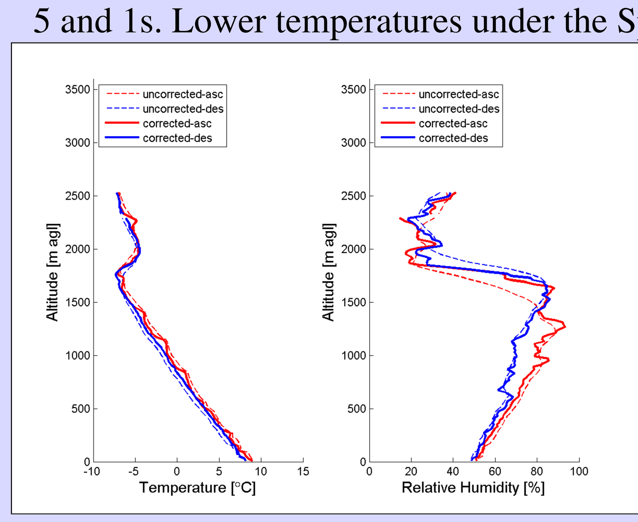

Figure 5: Corrected and uncorrected profiles of temperature and relative humidity. Measurements are taken North of Hofsjökull during the FLOHOF campaign on Iceland, 18.08.2007 17:56 UTC.

Numerics

The basic assumption behind the presented correction scheme is that the time change of the sensor output signal is proportional to the difference between the instantaneous *measured* parameter value (y) and the *ambient* parameter value (x), i.e.:

$$\frac{dy}{dt} = -\frac{1}{\tau_s} \cdot (y - x) \quad [1]$$

y = sensor value
x = ambient value
τ_s = time constant of the sensor

A Laplace transformation gives the general solution of eq.[1]:

$$y(t) = \frac{1}{\tau_s} \int_{-\infty}^{t} x(s) \cdot \exp\left(\frac{s-t}{\tau_s}\right) ds \quad [2]$$

This is a low pass filter and is aproximated very well by a *digital recursive Filter*:

$$y(t) \cong q_s \cdot y(t-\Delta t) + (1-q_s) \cdot x(t) \quad [3]$$
$$q_s = \exp(-\Delta t / \tau_s)$$

Equation [3] can be solved for the ambient value x giving the equation

$$x(t) = \frac{y(t) - q_s \cdot y(t-\Delta t)}{1-q_s} \quad [4]$$

With this *digital recursive filter* the ambient values $x(t)$ can be ***reconstructed*** from only two subsequently measured values $y(t)$ and $y(t-\Delta t)$.

The solution is very sensitive to noise in $y(t)$ (derivation of a noisy signal). Accordingly the signal y has to be smoothed, e.g. with eq.[3] and an additional time constant τ_f

Wind profiles

One additional benefit of the SUMO system is its ability to provide wind profiles without using any onboard flow sensor. Approximately constant true air speed can be assumed by flying the aircraft during ascent and descent in autonomous mode with fixed throttle and pitch. Wind speed and wind direction can then be determined from the data on speed above ground provided by the autopilots GPS system (Fig. 5).

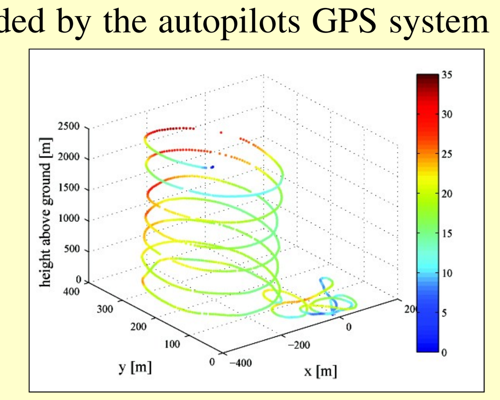

Figure 5: Descent trajectory of a typical, helical flight pattern used for profiling the atmospheric boundary layer. The colors indicate the ground speed of the aircraft given in m/s. The measurements have been performed North of Hofsjökull during the FLOHOF campaign on Iceland, 18.08.2007 17:56 UTC.

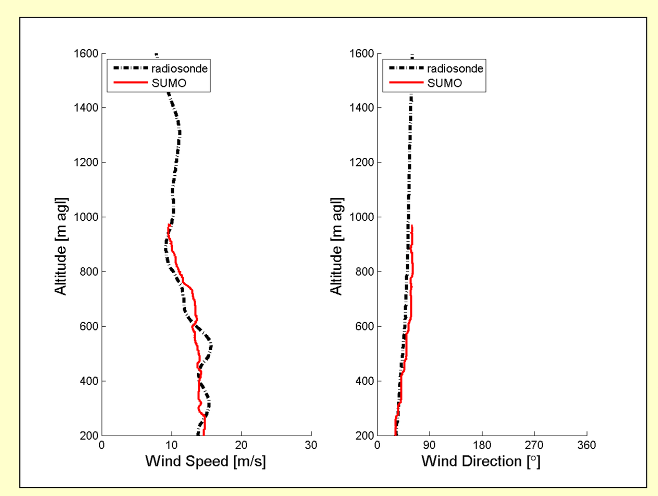

Figure 6: Profiles of wind speed and direction derived from a SUMO ascent performed from the helicopter deck of the Norwegian Coast Guard vessel KV Svalbard at 76.74 °N and 18.25 ° E in the marginal ice zone on 28.02.2008. (Take-off SUMO: 15:11; launch of radiosonde: 15:15 UTC)

Intercomparison

A validation of the SUMO data has been performed by intercomparison with two established profiling systems. SUMO has been operated parallel with the remotely controlled UAV KALI (Egger et al., 2002) at several days of the FLOHOF campaign on Iceland. During the THORPEX campaign around Spitsbergen, profiles taken by a Vaisala RS92 radiosonde could be used for validation purposes.

Three examples of these intercomparisons are shown in the figures below. Both the SUMO temperature (Figs. 7 and 8) and wind profiles (Fig. 6) show a very good consistency with the profiles of the well established reference platforms. The profiles of relative humidity reveal somewhat larger discrepancies. This could be caused by the differing time constant of the humidity sensors in use. Moreover humidity is known to feature high variability in space and time, especially over highly inhomogeneous terrain. SUMO measurements in both regions, the surrounding of Hofsjökull and the marginal ice zone around Spitsbergen, have documented this high variability.

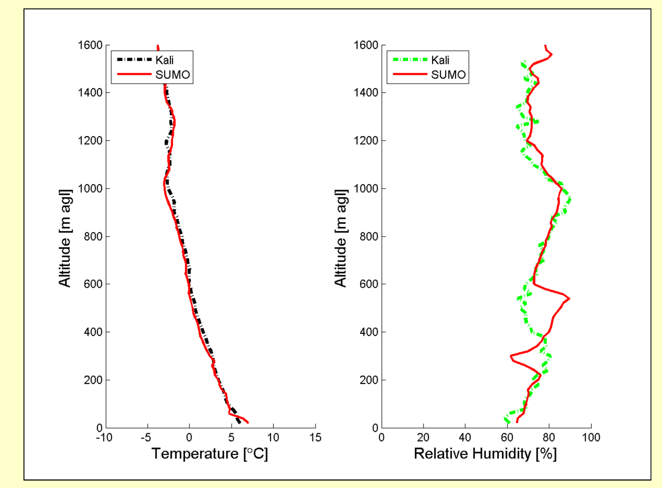

Figure 7. Profiles of temperature and relative humidity performed during the FLOHOF campaign at 65.00 °N and 18.90 °W, North of Hofsjökull on 17.08.2008. (Take-off SUMO: 11:03; Take-off Kali: 11:04 UTC)

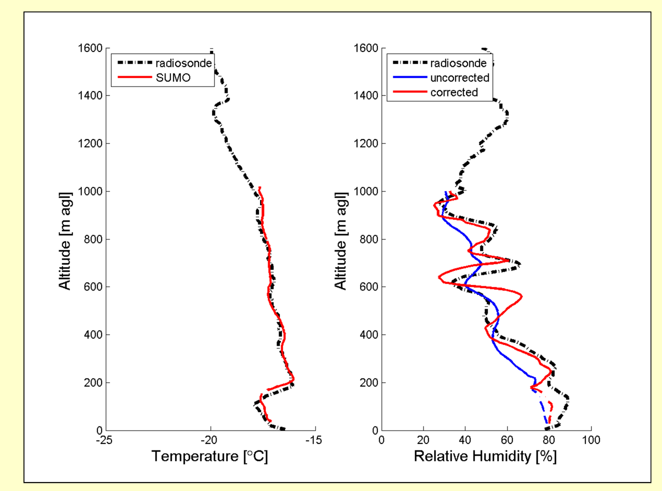

Figure 8: Profiles of temperature and relative humidity performed from the helicopter deck of the Norwegian Coast Guard vessel KV Svalbard at 76.74 °N and 18.25 °E in the marginal ice zone on 28.02.2008. (Take-off SUMO: 15:11; launch of radiosonde: 15:15 UTC)

References

Brisset P 2006 The Paparazzi solution. http://www.recherche.enac.fr/paparazzi/papers 2006/mav06 paparazzi.pdf

Egger J et al 2002 Diurnal winds in the Himalayan Kali Gandaki valley. Part III: Remotely piloted aircraft soundings Mon. Wea. Rev. 130 2042

Acknowledgement

The authors are grateful for the work of Martin Müller, Christian Lindenberg, Pascal Brisset and the other Paparazzi members that have made the SUMO project possible through their assistance and provision of their system as a whole with aircraft, hardware and software. The authors would also like to personally thank Michael Kislat for his support as a safety pilot during the campaign on and around Spitsbergen. The extensive in-field testing during August 2007, would not have been possible without the FLOHOF campaign funded by the German Research Foundation under contract EG 40/25-1. The main financial support for the development of SUMO was provided by the Meltzer University Foundation, Bergen, Norway. The comprehensive testing of the system in the Arctic, spring 2008 would not have been possible without the personal stipend of the main author granted by the Norwegian Polar Institute and financial support provided by the Norwegian IPY-THORPEX campaign. We would also like to thank the crew of the Norwegian ice-breaking, coast guard vessel KV Svalbard for their assistance during the research cruise to Storfjorden.

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