EUFAR Workshop Turbulence & Thermodynamics

Braunschweig, Germany
27th February to 2nd March 2007

Meeting Report:

1. Introduction

The meeting of the two EUFAR Expert Working Groups on 'Turbulence Measurements' and on 'Thermodynamics' took place in Braunschweig at the Institute of Flight Guidance of the local Technical University from 27th February to 2nd March 2007. The workshops for both working groups have been merged due to the fact that many issues are covered by both EWGs. Particularly the EUFAR activities in the area of 'Turbulence Measurements' have been hereby increased.

Up to 21 experts from Germany, Italy, Spain, Switzerland, the UK and the USA attended the workshop and formed a well mixed group of scientists, users of research infrastructure, operators of research aircraft and developers of new instrumentation.

Two sessions for turbulence and thermodynamic issues and a third common discussion part were put on the agenda. Within the first two sessions an overview about new research platforms, present instrumentation and sensor developments, current/past campaigns, scientific needs and existing problems was given in short presentations of the attendees. These talks provided the basis for the succeeding discussion that resulted in suggestions and ideas for future activities and recommendations to the scientists, aircraft operators and funding agencies.

2. PRESENTATIONS

The participants had been asked to present several talks within the area of their expertise.

During the turbulence part several presentations dealt with outcomes/results of turbulence measurements. Turbulence especially small scale turbulence measurements depend on slow flying platforms to get rid of dynamic pressure effects. On this account mini unmanned air vehicles as new platforms and their prospect for turbulence measurements had been introduced. Also existing platforms like the helicopter-borne ACTOS and Helipod or the two aircraft ECO-Dimona and Grob Egrett had been presented where these talks primarily focused on instrumentation ideally equipped for the use for turbulence purposes. Several critical annotations from a user's point of view mainly started the discussion on these topics.

An outlook on the new high altitude and long range research aircraft HALO as a platform for thermodynamic measurements had been given by one talk to the audience in the second part of the meeting. The following talks were devoted to research projects, sensor developments and calibration techniques. Campaigns like MOZAIC or CARIBIC that use commercial passenger aircraft as platforms had been presented. It had been pointed out in several talks of this session that dynamical and thermodynamical measurements in clouds – especially temperature – are still long-standing problems which have to be discussed. Calibration techniques and facilities for hygrometers and the development of new sensors and systems had been presented.

Summarizing, the presentations are listed in the following tables:
(You can click on the presentation title to get directly to the abstract)

WORKSHOP ON TURBULENCE (SESSION I)

Jens Bange	Calculation of area-representative turbulent fluxes above heterogeneous terrain from low-level flights using inverse models (*not been held due to illness*)
Aline van den Kroonenberg	Truncation of meso-scale motions from airborne atmospheric turbulence measurements using multi-resolution decompostion
Matthias Cremer	Turbulence and wake vortex Measurement with the Dornier 128-6
Oscar Serrano Vargas	Turbulence & Thermodynamic on INTA aircraft
Markus Quante	Airborne turbulence measurements in the free troposphere: Annotations of a partly involved user
Jens Bange & Aline van den Kroonenberg	Turbulence measurements with the mini UAV 'M²AV Carolo' - First results and outlook
Bruno Neininger	MetAir and ARA: Another overview and hopefully some news on turbulence & thermodynamics
Holger Siebert	Small-Scale Turbulence Measurements in Clouds
Phil Brown	The EUFAR activities

WORKSHOP ON THERMODYNAMICS (SESSION II)

Andreas Giez	Basic Thermodynamic Measurements on DLR Aircraft
Martin Zöger	Ready for HALO, Improved Water Vapour Calibration Bench
Mark Zondlo	Calibrations of the VCSEL hygrometer for the NSF HIAPER aircraft
Herman Smit	On the performance of the airborne MOZAIC-Humidity Device: Ten years of in-flight and laboratory experience
Rex Fleming	Status of Moisture Measurements on Commercial Aircraft And Expected Future Products for Mobile Platforms
Andreas Zahn	Measurement of water vapour and total water onboard passenger aircraft, project CARIBIC
Herman Smit	About the Performance of the Water Vapour Sampling System (WVSS-II): Results from tests at the environmental simulation facilty at Jülich
Axel Hoff	Humidity Sensor Enters the European AMDAR Fleet
Martin Zöger	Error Sources of Airborne Temperature Measurements
Phil Brown	In-cloud temperature measurements: Science requirements and current limitations
Rex Fleming	Toward a More Accurate Temperature Sensor for Mobile Platforms
Mark Zondlo	Fast temperature measurements using tuneable diode lasers

Abstracts

Calculation of area-representative turbulent fluxes above heterogeneous terrain from low-level flights using inverse models (Jens Bange)

The low-level flight method (LLF) has been combined with linear inverse models (IM) resulting in an LLF+IM method for the determination of area-averaged turbulent surface fluxes. With this combination, the vertical divergences of the turbulent latent and sensible heat fluxes were calculated from horizontal flights. The statistical errors of the derived turbulent surface fluxes were significantly reduced. The LLF+IM method was tested both in numerical and field experiments. Large-eddy simulations (LES) were performed to compare true flux profiles with measurements of simulated flights in an idealised convective boundary layer.

The LLF+IM method was then applied to data collected during two flights with the Helipod, a turbulence probe carried by a helicopter, and with the research aircraft Do128 in the LITFASS-98 field campaign. The derived surface fluxes were compared with results from eddy-covariance surface stations and with large-aperture scintillameter data. The comparison showed that the LLF+IM method worked well for the sensible heat flux at 77 and 200 m flight levels, and also for the latent heat flux at the lowest level. Finally the LLF+IM method was applied to more than twenty low-level flights from the LITFASS-2003 experiment.

Comparison with aggregated surface flux data revealed good agreement for the sensible heat flux but larger discrepancies and a higher statistical uncertainty for the latent heat flux.

☞ To the presentation

Truncation of meso-scale motions from airborne atmospheric turbulence measurements using multi-resolution decompostion (Aline van den Kroonenberg)

Airborne measurements in the Arctic stable boundary layer were performed using the helicopter-borne turbulence measurement system Helipod. The observations were carried out during the ARK-XII summer expedition of the research icebreaker Polarstern in the Arctic Ocean. The boundary layer over closed sea ice exhibited mainly weakly stable stratification.

Only flights in continuous turbulence were chosen for the analysis. The measurements of sensible heat flux H and latent heat flux E were made 200 km away from land to reduce the influence of any captured mesoscale flux. Nevertheless, the analysis of multiresolution (MR) cospectra yield some small mesoscale flux contribution, visible at the larger time scales. A MR gap time scale gap was defined to separate the turbulent flux from the mesoscale flux and used for the re-calculation of the turbulent fluxes after high-pass filtering.

This procedure also reduced the statistical error of the fluxes significantly.

For comparison, wavelet transformations were performed that led to wavelet gap scales of the fluxes in good agreement with the MR gap scale. Additionally, the wavelet covariance gave a good representation of the homogeneity of the kinematic heat flux and the kinematic moisture flux in time.

☞ To the presentation

Turbulence and wake vortex Measurement with the Dornier 128-6 (Matthias Cremer)

The Dornier 128-6 is equipped with a scientific instrumentation which is specialized for meteorological measurements in the lower atmosphere. The standard instrumentation consists of a nose boom which contains all main meteorological sensors such as temperature, pressure, humidity and airspeed-vector (wind-vector). Additional wind measurement stations are installed on each wind tip and the vertical stabilizer. The position and attitude of the aircraft is obtained by the Global Position System (GPS) and an inertial laser navigation platform. Specific scientific instrumentation can be installed inside the cabin such as air chemical sensors, meteorological drop sondes or an airborne gravimeter.
As example for the wind and turbulence measurement system a wake vortex encounter flight test is explained. A smoke generator was installed on the ATTAS to visualize its wake vortex. The Dornier 128-6 performed encounter flights from each side and from top. The four wind measurement stations measured the vortex field with a small local resolution. It showed peaks in the vertical wind component of about 15 m/s within a distance of 1 to 2 m. During the flight test roll angles of up to 80° were reached.

The results were used in the "s-wake" project for the validation of wake vortex models.

- To the presentation

Turbulence & Thermodynamic on INTA aircraft (Oscar Serrano Vargas)

Unfortunately, there is no abstract available for this presentation.

To the presentation

Airborne turbulence measurements in the free troposphere: Annotations of a partly involved user (Markus Quante)

Unfortunately, there is no abstract available for this presentation.

To the presentation

Turbulence measurements with the mini UAV 'M²AV Carolo' - First results and outlook (Aline van den Kroonenberg / Jens Bange)

The limitations of manned airborne meteorological measurements led to a new unmanned system, the Meteorological Mini-UAV (M²AV), recently developed by the Institute of Aerospace Systems, Technical University of Braunschweig. The task was to develop, test and verify a meteorological sensor package as payload for an already available carrier aircraft, the UAV 'Carolo T200'. Thereby the limitations in size and mass had to be respected. The M²AV is capable of performing turbulence and wind vector measurements within the atmospheric boundary layer and permits very short measurement cycles as an economic supplement during meteorological campaigns. The talk gives details on the technical items. Results from meteorological data sets measured by the M²AV are used for data quality assessment. In October 2005 the M²AV participated in the meteorological field experiment LAUNCH-2005 in Lindenberg near Berlin. The M²AV data were compared with lidar and sodar measurements. Furthermore, an in situ comparison of temperature, humidity and wind vector data with the helicopter-borne turbulence probe Helipod was analysed and gave information about the M²AV data quality.

To the presentation

MetAir and ARA: Another overview and hopefully some news on turbulence & thermodynamics (Bruno Neininger)

The development of sensors and platforms at MetAir (1 Dimona) and ARA (Airborne Research Australia; 2 Dimonas and an Egrett) was presented in an overview. There was a focus on some aspects of post-processing including optimisation of 3-d wind measurements. The conclusion was that we prefer to use each flight as an in-flight calibration instead of deducing from laboratory calibrations. This is not "better", but, the only way we can cope with the whole chain from the sensor characteristic until the interference with the platform. The results are quite good (see e.g. the consistence of individual 1- and 10-Hz wind vectors in slide 15). Another aspect was humidity measurements with a combination of "slow" (1 Hz) and accurate dew point measurement, and fast (10 to 20 Hz) IRGA (LI-7500). Finally I discussed a problem with the original FUST probe from the NOAA BAT family of sensors. We detected a problem with the coupling of the reference temperature and the reference junction which can either be fixed with thermal conducting compound, or a re-design.

There are many issues of turbulence & thermodynamics which would be suitable for a JRA initiative for a EUFAR follow-up under FP7.

☞ To the presentation

Small-Scale Turbulence Measurements in Clouds (Holger Siebert)

Small-scale processes in clouds as turbulent mixing at cloud edges or cloud top (so-called "entrainment") play a major role for the development and life time for all kind of atmospheric clouds. In-cloud mixing is supposed to be one key factor in the development of larger cloud droplets and, therefore, for the onset of precipitation. However, research aircraft for cloud observations are fast-flying platforms which are currently not suitable for making turbulence measurements with a spatial resolution of better than one meter or so. In order to increase the spatial resolution a helicopter with the measurement payload ACTOS (Airborne Cloud Turbulence Observation System) is used for turbulence measurements with at least decimeter resolution. ACTOS is fixed at a 140-m long tether rope below the helicopter to overcome the influence of the helicopter downwash. This setup is used for measurements in shallow cumulus or/and stratiform clouds. The sensor equipment and the general setup of the helicopter-ACTOS combination are introduced and preliminary results are shown.

☞ To the presentation

Basic Thermodynamic Measurements on DLR Aircraft (Andreas Giez)

The German Aerospace Centre (DLR) with its two flight facilities in Braunschweig and Oberpfaffenhofen operates one of the largest fleet of research aircraft in Europe. The DLR Flight Facility Oberpfaffenhofen is exclusively focussed on the support of scientists in the fields of environmental research, meteorology and earth observation providing three aircraft with different flight envelopes and modifications for this task.

The presentation gives an introduction to DLR and its facilities. The Oberpfaffenhofen based research aircraft and their permanent thermodynamic sensor installation are presented explaining the sensor concept and measurement techniques as well as calibration and data processing issues. An outlook on the thermodynamic measurements on the new research aircraft HALO will close the presentation.

☞ To the presentation

Ready for HALO, Improved Water Vapour Calibration Bench (Martin Zöger)

A high precision water vapour calibration bench was developed at DLR Research Flight Facility. The calibration bench allows simulating the complete atmosphere from ground to stratosphere with respect to humidity and pressure. The humidity is controlled by mixing humid and dry air. A high precision dew point mirror is used as reference instrument and regularly certified by PTB. This calibration bench was modified recently improving accuracy and handling. This was mainly achieved by implementing a new humidifier based on a thermoelectric temperature controlled condenser and replacing the reference instrument with a new advanced instrument from MBW. The calibration bench is fully computer controlled and can perform automatic calibration from file. To demonstrate capabilities of the calibration bench combined with the climate simulation chamber of DLR measurements of temperature dependence of the sensitivity of a Vaisala relative humidity sensor are shown.

☞ To the presentation

Calibrations of the VCSEL hygrometer for the NSF HIAPER aircraft (Mark Zondlo)

Water vapor plays major roles in the climate, dynamics, and chemistry of the Earth's atmosphere. These roles are especially important in the upper troposphere and lower stratosphere where subtle changes in the amount of water vapor have enormous implications on cloud microphysics, troposphere to stratosphere exchange, ozone chemistry, and the radiative budget of this region. Unfortunately, water vapor is extremely challenging to measure with at times significant disagreements between sensors. Measurement challenges of water vapor include its great variability in the atmosphere, efficient adsorption to instrument surfaces, and six orders of magnitude range in absolute concentration.

To this end, a new hygrometer is being developed for NSF's HIAPER (High-performance Instrumented Airborne Platform for Environmental Research) Gulf-stream-V aircraft that can overcome many of these challenges, in addition to size, mass, and sampling constraints for such a relatively small but high-speed aircraft. The key innovation is the use of a recently-developed vertical cavity surface emitting laser (VCSEL) which allows multiple absorption lines of water vapor to be probed at high frequencies with a single laser. The HIAPER VCSEL hygrometer will measure water vapor from 1 to 40,000 ppmv at a sampling frequency of 25 Hz with < 3% precision and <=5% accuracy. The rationale and design of the sensor will be discussed, followed by laboratory experiments on its accuracy, precision, calibration, and noise characteristics. Future test flight plans will also be discussed as part of NSF's PACDEX and DOE's MASE field experiments.

☞ To the presentation

On the performance of the airborne MOZAIC-Humidity Device: Ten years of in-flight and laboratory experience (Herman Smit)

Within the MOZAIC (Measurement of ozone, water vapour, carbon monoxide and nitrogen oxides by Airbus in-service aircraft) programme the large scale distribution of water vapor is measured since August 1994 onboard of five Airbus A340 aircraft during scheduled flights operated by civil airlines (Marenco et al. 1998). The compact airborne sensing device used in MOZAIC for the measurement of relative humidity (capacitive sensor) and temperature (PT100-sensor) is mounted in a Rosemount TAT housing.
The sensors are calibrated in the laboratory before and after 500 hours of flight operation. From the regular pre-and post flight calibration of each flown sensor typical 2σ-uncertainties of ±(5-10) relative humidity between 9 and 12 km altitude were derived. The in-flight performance of the MOZAIC-humidity device had been assessed by several intercomparison with reference instrumentation during dedicated aircraft missions and confirmed the results yielded from pre-and post calibrations. The response time of the humidity sensor at cruise altitude is about 1 minutes such that, at an aircraft speed of 250 m/s, the horizontal resolution is about 15 km while the vertical resolution is about 250 m. The temperature can be measured with an accuracy of about ±(0.5-0.7) K and a precision better than ±(0.1-0.2) K.

☞ To the presentation

Status of Moisture Measurements on Commercial Aircraft And Expected Future Products for Mobile Platforms (Rex J. Fleming)

The second generation water vapor sensing system (WVSS-II) for commercial aircraft and other mobile platforms [commercial, business, and military aircraft; unmanned aerial vehicles (UAVs); and other mobile platforms] has now gained considerable operational experience. The WVSS-II is a diode laser system for measuring atmospheric water vapor mixing ratio – a far superior system for measuring water vapor information than from thin film capacitors used to measure relative humidity.

The results are summarized (including manufacturing pitfalls that have been discovered and fixed). There are a number of conclusions that can be made for the use of such systems both for near term aviation interests, weather prediction in general, and for climate change assessment that will be presented.

Future follow on products are a natural progression of the existing and near-term technology that can be expected to be available. These are discussed as time permits.

☞ To the presentation

Measurement of water vapour and total water onboard passenger aircraft, project CARIBIC (Andreas Zahn)

Unfortunately, there is no abstract available for this presentation.

☞ To the presentation

About the Performance of the Water Vapour Sampling System (WVSS-II): Results from tests at the environmental simulation facilty at Jülich (Herman Smit)

Recently, a new compact aeronautical water vapour sensor based on tunable diode laser spectroscopy (WVSS-II, Spectra Sensor Inc., USA) designed for implementation in AMDAR onboard of commercial aircraft has become available. In collaboration with the German Weather Service (DWD) and E-AMDAR we have investigated the performance characteristics of the WVSS-II sensor in our environmental simulation chamber at Research Centre Jülich (FZJ) through comparison against accurate Lyman (alpha) hygrometer at low humidities (5-2000 ppmv) and a frost point hygrometer for higher humidities (1000-40,000 ppmv). The investigations have particularly focused on the characteristics and performance of the new sensor in terms of precision, accuracy and stability at varying pressure, temperature and humidity levels, particularly for the UT/LS region at water vapor mixing ratios of 5 -100 ppmv).
A total of 11 simulation experiments whereby pressure, temperature and frost point temperature were varied in the same fashion as they are typically observed during aircraft flights between surface and up to 12 km altitude. At moderate humidity levels (200-30000 ppmv) typical for lower and middle troposphere the performance is good with relative accuracy of WVSS-II is ±(5-10) %. However, particularly at water vapor mixing ratios below 100 ppmv the accuracy of WVSS-II is declining rapidly. It is concluded that the WVSS-II sensor can be sufficient for humidity measurements in the

lower and middle troposphere but not suitable for upper tropospheric and lower stratospheric measurements.

☞ To the presentation

Humidity Sensor Enters the European AMDAR Fleet (Axel Hoff)

Apart from conventional measurements, meteorological data are also won by commercial aircraft during the routine flight climbing, cruising, and descending within an altitude range between ground and 12,000 m. This kind of network has the name AMDAR (Aircraft Meteorological Data Relay). The measurements are transmitted world-wide in near real-time via radio connection to the airline's data centres who forward them to the national meteorological services. The data consist of messages with

- identification number, date and time,
- position and flight altitude (here equivalent to the ambient air pressure),
- air temperature, wind velocity and wind direction.

The European consortium E-AMDAR (EUMETNET AMDAR) under participation of the DWD among 13 further European weather services is processing

- more than 30,000 meteorological aircraft messages daily,
- of 530 activated airplanes (Air France, British Airways, KLM, Lufthansa and SAS)

Up to now there still are some data sparse areas over the world. Moreover, another important parameter being very crucial for the weather forecast still was missing so far: the humidity.
Until late 2006, the sensor system WVSS II (SpectraSensors Inc., USA) has been installed into three Lufthansa aircraft of the Airbus A320 family. The sensor's location is nearly 5 m behind the nose and on the 4 o'clock position on the body's circle section. The system's output of water vapour mass mixing ratio is integrated into the AMDAR data flow. This modification of the fleet contributes to a prospectively world-wide completion and partly replacement of the meteorological radiosondes.
The sensor's physical principle is based on the Tunable-Diode Laser spectroscopy. The amount of airflow through the sensing chamber and the air pressure there is kept within limits by the system's UCAR air sampler being flush mounted on the fuselage. The actual WVSS II version is equipped with a heated inlet hose. This technical precaution prevents unwanted condensation processes in the upstream section between the air sampler unit and the sampling tube.
First results of the flight operation show a reasonable congruence with adjacent radiosonde data. Laboratory test results as well as flight operational experiences in the USA and Germany lead to some ideas about the improvement of the operational principle. The key points of desired system's modifications are addressed.

☞ To the presentation

Error Sources of Airborne Temperature Measurements (Martin Zöger)

Precise airborne temperature measurements still are a challenge. An overview about different methods of airborne temperature measurements will be given. The following error discussion is based on the systems used at DLR Research Flight Facility and therefore mainly focuses on 'classic' total air temperature measurement. Error sources of airborne temperature measurements are manifold and are separated in two classes: 'static errors' e.g. from calibration and the complete measurement chain and 'dynamic errors' caused by the aerodynamic effects of the aircraft and the sensor itself. A more or less complete list of known error sources will be given summing up to an total error of 0.3 K – 0.5 K which has to be assumed as the current Status Quo in airborne temperature measurements.

☞ To the presentation

In-cloud temperature measurements: Science requirements and current limitations (Phil Brown)

The RICO (Rain In Cumulus over Oceans) field campaign was conducted in Jan 2005. One of the aims of this project was to sample the dynamical and thermodynamical characteristics of cumulus cloud updraughts and their environment. Specifying these differences is a key part of some schemes that are used to parametrize convective transports of heat and moisture in large-scale atmospheric models. Existing parametrizations have been obtained largely from high-resolution numerical models and there is a clear need for in-situ data with which to validate them.

On the majority of RICO aircraft, high-frequency temperature measurements were obtained with either Rosemount or reverse-flow type immersion temperature sensors. These have been shown to suffer from characteristic biases within and on exit from clouds. These issues are normally referred to as "sensor wetting" although they are not necessarily related directly to the impact of cloud droplets on the temperature sensing elements. RICO measurements demonstrate the two main biases, which are: (i) a low bias when in the presence of liquid water, and (ii) a negative spike in temperature when leaving cloud. The latter is though to be a wet-bulb effect that is made worse by the build up of sea-salt accretions on the sensor element by prolonged flight at low altitude and/or in high-wind conditions.

A radiometric temperature sensor was also operated on the NCAR C-130 during RICO. Measurements from this device suggest 4 times more positively-buoyant regions within cloud and 5 times more positively-buoyant updraughts than are obtained using immersion temperature sensors. However, such radiometric measurements are averaged over path lengths that are spatially-separated from turbulent wind fluctuations and so are unsuitable for eddy-correlation turbulent flux measurements. This demonstrates a continued need for improved in-cloud temperature measurements that are unaffected by the presence of cloud water.

A further driver for in-cloud temperature measurements comes from the need to understand water-vapour distribution within ice clouds. These can support significant sub-and super-saturations that are not found in water clouds, due to the lower rates of vapour diffusion to/from the ice cloud particles. Estimation of relative humidity within cloud to better than 5% requires an absolute temperature accuracy of better than 0.4K at typical cirrus cloud temperatures.

☞ To the presentation

Toward a More Accurate Temperature Sensor for Mobile Platforms (Rex J. Fleming)

The total air temperature (TAT) probe on commercial aircraft has been virtually unchanged since its incorporation on jet aircraft about 50 years ago. The total air temperature measured includes the outside or ambient atmospheric temperature plus the additional heating of the air due to the kinetic energy of the fast moving aircraft. However, over the past several years with the advent of ever greater numbers of atmospheric temperatures being derived in real time from the TAT probe and greater attention being paid to the data, there has been a growing concern among atmospheric scientists of the TAT probe temperature errors. These errors involve both random error and systematic biases that vary from aircraft to aircraft.

There are four negative attributes of the TAT probe that can be removed with a flush mounted air sampler and temperature measurement system. These attributes are the lack of accuracy, the required heater for the probe, the additional drag due to the probe, and the increased radar cross section – undesirable for many military aircraft today. The elimination of the TAT probe involves several hardware and software processes which are now patent protected.

This presentation describes these processes that lead to a measurement system working within the atmospheric/aircraft boundary layer (1-2 cm away from the skin) of a fast moving aircraft or any mobile platform moving at a velocity less then the speed of sound. Simulation results and wind tunnel test results are shown. Actions required to complete the testing are suggested.

☞ To the presentation

Fast temperature measurements using tuneable diode lasers (Mark Zondlo)

Fast temperature measurements are critical for understanding turbulence, cloud microphysics, and energy fluxes, among others. Sampling at fast frequencies requires minimal perturbation to the sampled airstream. Tuneable diode lasers have the potential to offer open-path measurements which have very minimal sampling artifacts. This talk explores potential atmospheric species that can be used as proxies to obtain temperature measurements and evaluates their usefulness in the atmosphere. In particular, oxygen absorption lines near 760 nm offer an intriguing possibility to obtain fast relative temperature measurements. Two methods are explored - one using peak ratios and one using integrated direct absorbances. Both methods use vertical cavity surface emitting lasers near 760 nm that have wide tuning ranges. Although absolute precision may be difficult in the short-term, relative temperature measurements of 0.1 K at 10 Hz are possible for aircraft-based platforms and an order of magnitude improvement is possible for more "static" pressure environments such as on ground-based platforms.

☞ To the presentation

3. DISCUSSION

Understanding of turbulence

That the expression “turbulence” can be understood differently has been shown in the variety of the talks in the presentation session. Turbulence is defined as the flow of a liquid or gas including random variation of pressure and velocity in space and time. Therefore it had been made a distinction between (small-scale) atmospheric turbulence measurements and measurements of wake vortices.

Wake turbulence is turbulence that forms behind an aircraft as it passes through the air. Wake vortices are relative stable and can remain in the air for up to two minutes after the passage of an aircraft. They are a big and very dangerous problem in aviation. Wake turbulence is especially hazardous during the landing and takeoff phases of flight, for two reasons. The first is that during take-off and landing, aircraft operate at low speeds and high angle of attack. This flight attitude maximizes the formation of dangerous wingtip vortices. Secondly, takeoff and landing are the phases of flight when a plane is operating closest to its stall speed and to the ground - meaning there is little margin for recovery in the event of encountering a different aircraft's wake turbulence.

Atmospheric turbulence is caused by random fluctuations in the wind flow. It can be caused by thermal or convective currents, differences in terrain and wind speed, along a frontal zone, or variation in temperature, humidity and pressure. As defined in the EWG meeting 2002 in Capua, scales that are smaller than 10m down to the Kolmogorov scale of order of 1mm are considered to be small-scale turbulence.

During the discussion it had been detected that there is still an unsatisfied demand for documentation of turbulence measurements, especially of students and junior scientists visiting the EUFAR website and not knowing about measuring turbulence. It has to be clarified what constitutes “turbulence measurements”. It would be helpful to have a compendium of measurement techniques in use on the EUFAR fleet. This would implicate a detailed description of the used sensors (accuracies, resolutions, time response, limitations…), measurement platforms as well as data processing and calibration techniques. There also should be a list of references/literature available on the EUFAR website.

Platforms & instruments in use for (small-scale) turbulence measurements

The choice of the most capable platform to measure turbulence is depending on the application. The decision can only be made by clarifying, which scales and parameters in which altitudes is the interest in. In general, only slow flying platforms (< 100m/s) equipped with close collocated fast sensors and data acquisition systems capable of recording very high frequency data (> 100Hz) can perform turbulence measurements at very small scales.

Different platforms and instrumentation had been introduced to the audience during the first part of the workshop (see presentations and abstracts).

An example of clever sensor design is the Ultra-Fast Thermometer (UFT) installed on the helicopter-borne platform ACTOS of the IFT Leipzig which was developed at the University of Warsaw. As it is known, the most fast response thermometers are based on fine-wires. In this case the sensing element consists of a platinum-coated tungsten wire. With its 2.5 µm in diameter and 5 mm length the wire allows sampling frequencies of up to 10 kHz. While measuring in clouds impacting cloud droplets can destroy the sensing wire. Another problem is the evaporative cooling. Therefore a shielding rod is installed in front of the sensing wire which prevents an impact of cloud droplets on the sensing wire itself. Nevertheless, due to its exposed/open design the use of the sensor is limited to low velocities and warm non raining clouds.

Temperature sensors of the Rosemount type (now manufactured by B.F.Goodrich Aerospace) are commonly used on the faster turboprop or jet aircraft. The presence of the sensor housing around the sensor element itself has a damping effect on the sensor response that has been documented. In addition, the application of de-icing heating produces a measurement bias that requires correction (as detailed in the presentation by Martin Zoeger, above). Software procedures for correcting the de-ice heating bias and the high-frequency response of Rosemount sensors exist and should be used in any attempts to calculate turbulent heat fluxes. However, there remains a requirement for improved fast-response temperature sensors that are sufficiently robust for operation on high-speed aircraft (100 m/s and above).

Generally, a sampling rate of 100 Hz is state of the art for turbulence measurements which offers a measurement of fluctuations with spatial resolution down to 1 meter scale. The slower the airspeed the better is the spatial resolution. 1 kHz measurements are already available for temperature, drop spacing and liquid water content.

To have a relative accuracy for wind velocities less than 0.05 m/s and a relative accuracy of temperature fluctuations less than 0.01 K with sampling rates better than 100 Hz also <u>at high aircraft speeds</u> (> 100 m/s) will be the most challenging task in sensor development.

During the discussion it has been remarked that there could be a demand of a common system package like the DLR pod “penguin” for turbulence measurements within the EUFAR community. It has to be carefully deliberate if the development of such a system package would be able to be used for all aircraft of the European fleet. Certification, calibration and check of the operability on different aircraft are only some of the mentioned problems that have to be analysed.

Acquisition and processing of data – quality management

As also users of research structure joined the workshop some wishes had been expressed concerning the measurements and outcomes of research flights. They would like to receive assistance of the aircraft/platform operators. The acquired data have to pass some kind of quality check to make sure that the data are reliable. Quality insurance – this is necessary to do! A possible way could be by marking erroneous measurements with error flags. There is also a strong need for documentation of measurements, how the data have been calculated from the raw data (correction factors, alternative processing, units, etc.). A detailed description of system characteristics, sensor response characteristics, information about calibration techniques as well as date and time of last calibration should be included in the documentation which the operators have to provide and kept up to date.

A good example of such documentation is shown for temperature measurements by Martin Zoeger (above). Turbulent wind measurements typically involve the combination of measurements from multiple sensors, for example, (i) GPS for low-frequency aircraft position and velocity, (ii) Inertial Navigation Systems for aircraft velocity, attitude and attitude rate-of-change, (iii) differential pressure measurements for airflow incidence angle and dynamic pressure, (iv) temperature (and ideally also humidity) for conversion of dynamic pressure to true airspeed. The propagation of errors through such a system is complex to describe and document.

Users should insist on this documentation!

To avoid lost flight hours there should be an intensive information exchange of operators and users in advance which should also be an iteration process. It has to be made clear that the chosen platform and the installed instrumentation are capable to perform well for the intended application. The decision process should also be accompanied by a visit of the facilities and operators, because there is still a gap in documentation on each website (only basic information) – otherwise the best choice of aircraft and instrumentation is not possible.

Operators within EUFAR should review their information on the EUFAR website. Each platform differs from the other ones in instrumentation and performance. Limitations of aircraft could be listed and neatly arranged on the EUFAR homepage. Also necessary is a detailed description of sensors in use of aircraft with indication of accuracy, response time, etc.

Finally, the development of common calibration procedures for each measurement method was discussed. Comparing existing calibration methods/facilities of sensors that are going around would be a first step to a “sensors tested by EUFAR certificate”. The attending operators of humidity calibration facilities signalled their readiness to make a comparison of their humidity calibration.

Temperature

Overview

Aerodynamic effects strongly influence airborne temperature measurements. Therefore measurement systems based on total air temperature measurements still are the most accurate once for aircraft flying at high and moderate speed. Remaining uncertainties in aerodynamic correction factors still limit the absolute accuracy of airborne temperature measurement to (0.3 – 0.5) K. Higher accuracies can only be achieved by redesign or better characterisation of known total air temperature sensors or development of new techniques. Currently there is now known activity in this field within EUFAR or even worldwide.

At aircraft speeds low enough to neglect aerodynamic influences exposed immersion type sensors are the best choice. Depending on the requirements for time response or robustness these sensors are based on thermistor, thermocouple or open wire sensors. Relative temperature sensors like thermocouples need a careful thermal design to avoid erroneous temperature measurements due to bad reference measurement (Bruno Neininger reported some bad experience with commercial sensors).

In-cloud measurements

Airborne temperature measurement within clouds still is a very challenging task. ‘Classic’ total air temperature housings are designed to separate particles and droplets from the sensor. Nevertheless total air temperature measurement within heavy water clouds show strong anomalies caused by droplet evaporation or sensor wetting. Also different approaches to overcome this problem designing special type of sensors like reverse flow to improve the particle separation did not succeed. Only a few remote sensing radiometric instruments exist allowing to measure temperature within heavy water clouds (see also presentation of Phil Brown). Unfortunately these instruments are quite bulky and difficult to operate. Due to its measurement principle radiometric instruments have a low time resolution and also need careful calibration outside of clouds. Therefore currently no ‘standard’ aircraft instrumentation exists capable to accurately measure temperature within heavy water clouds.

Attempts to correct affected temperature measurements e.g. by Met Office were not successful. Additional sensors like a cloud detector or a liquid water content sensor could help to identify ‘bad’ temperature data. To avoid misinterpretation of wrong in-cloud temperature measurements affected data ether have to be deleted or at least clearly marked as wrong data.

New approaches to measure in-cloud temperature based on optic or acoustic methods would be of great use for the EUFAR community.

Humidity

Overview

Within EUFAR a broad spectrum of different instruments exists to measure atmospheric water vapour. Many instruments have limitations making it necessary to combine several instruments to achieve good quality data. Chilled mirror instruments for example are known for their good accuracy, wide range and reliability but suffer from a tendency to overshoot strong gradients and the dew/frost ambiguity in the frost point range of (0…-40) °C. This ambiguity can induce an additional error in the dew point measurement of several K. IRGA instruments (Licor) need some modifications to work properly onboard aircraft and are limited in measurement range. Capacitive sensors suffer from temperature dependency of response time and need extensive calibration to extend the measurement range to the upper troposphere. Lyman-alpha absorption and photo-acoustic instruments need an in-flight reference instrument to achieve accurate measurements. Tuneable diode laser (TDL) instruments have the potential for reliable and accurate measurements over a wide measurement range but up to now no commercial instrument could fulfil the expectations.

One main output of this workshop is the table "***Humidity Measurement Methods***" giving an overview of different instruments with specifications and remarks based on the experience within the EUFAR Expert Working Group:

☞ To the table

Several international and European projects as well as the EUFAR community show strong interest in a compact and reliable instrument to measure water vapour in the Troposphere or even lower Stratosphere.

In-cloud Measurements

Airborne water vapour measurements are also affected by cloud particles entering the inlet. Total water vapour measurements intentionally collect cloud particles but need good characterisation of the inlet to correct for particle enhancement caused by aerodynamic effects. Gas phase water vapour measurements need careful inlet design to separate cloud particles. Even if the effect of the evaporation of remaining small cloud particles within the reverse flow inlet is less drastic for water vapour measurements then for temperature measurements nevertheless most water vapour measurements are strongly linked to air temperature since calculation of free air stream humidity from the measured humidity often needs temperature corrections.

A different approach to omit influence by cloud particles are open path instruments. In this case the measurement is outside the aircraft and not influenced by any contamination of the inlet or the measurement cell. But discussion showed that the effect of aerodynamic distortions caused by the aircraft and even more by the instrument itself where not investigated up to now. It is expected that aerodynamic effects cause strong pressure gradients along the measurement path. Corrections of this gradient using a single pressure measurement along the path probably are not satisfying and could reduce absolute accuracy and cause dependencies of the water vapour measurements from aircraft speed and attitude.

Humidity Measurement Methods

Sensors			Range of use in the atmosphere							Time Response	Accuracy	Resolution (Precision)	Reliability / Robustness	operational Limitations	Availability	Potential for development
			Altitude regions						Measured value							
Chilled mirror	GE		LT	MT[1]						LT: few seconds UT: minutes				Ambiguity between dew- and frost-point measurements at MT and UT temperatures		Improved chilled-mirror devices listed below.
	ML		LT	MT[2]						< 1sec 10s frost	0.3°C dew point which is about 0.1 g/kg in the range 2..10 g/kg	0.2°C or 0.05 g/kg	very good (I have it in service since 1979!)	needs cleaning best every day	easy, buy or borrow (several groups)	just improved noise by a factor of 6 in April 2007
	Buck	CR2	LT	MT	UT	LS			-100 to +30°C dew/frost	10 – 20s	+/- 0.1°C		Apparently low maintenance	Correction for difference between ambient and sample pressure (measurement option available). 10,000-hr lifetime of cryocooler unit	Commercial product.	Possible application of Stirling cycle cooling to miniature mirror to improve response time?
		CR1A	LT	MT	UT	LS			-120 to +30°C dew/frost	10 – 20s	+/- 0.1°C		Apparently low maintenance	Sample pressure correction – as CR-2. 6-8 hr duration of LN2 supply. Requires handling of cryogenic substances	Commercial product	
	SAW															
Humicap			LT	MT	(UT)					1s – minutes			Highly reliable – use on operational radiosondes and dropsondes	Temperatures sensitivity of calibration		
MOZAIC Humidity Device (MHD)			LT	MT	UT				LT: few sec. MT: 10-60 sec. UT: 1-2 min.	6% RH at Z=0-12km	0.5% RH	Highly reliable, compact in TAT-Housing; Automatic, calibration every 3 month	Not suitable for LS	Limited, Commercial	Reduction of maintenance, In-flight calibration (IFC)	
Ly-Alpha	abs.		LT	MT						0.01s	Absolute accuracy ~0.15 g/kg by calibration against reference device	Better than 0.01 g/kg	Source / detector tubes are fragile to handle but can be packaged. Maintenance required to refurbish tube windows	Requires a calibration source if absolute measurements are required. In the absence of this, it can be used for humidity flux measurements. Slow degradation of measurements due to opacity of source/detector tube windows. This can be recovered by simple polishing	Severely limited by availability of source and detector tubes	Newer source tubes avoid use of radioactive materials.

[1] Possible improved response of 1011C in UT
[2] Can operate 40deg below ambient temperature

	fluoresc.		MT	UT	<	S	>		1 – 10s						
IRGA (LiCor)	open (LI-7500)	LT	MT						0.05s	1 g/kg	0.02 g/kg	not too bad, but, it's fragile optics. There are some obvious interferences e.g. with aerosols.	sensitive to vibrations and fast pressure changes (see "potential"). Clean more frequently than asked by the manufacturer!	several in service	We modified the mounting, and got rid of the internal scrubbers. Active flushing with N2 gives better stability e.g. when descending from high altitude.
	closed (LI-6262)	LT	MT						1s	0.1 g/kg	0.01 g/kg	good	needs mods for airborne use	several in service	a few mods and operational precautions improve precision/accuracy considerably. However, the detection might remain insufficient for HT/LS
TDL	WVSS-II	LT	MT	UT					4Hz: avg to 2 sec	3-5%	N_1 . N_2 x 10^{-5} kg/kg	Designed for 2.5 year before recalibration	Mixing ratio range: 20 – 40,000 ppmv	Commercial product	Next generation being developed for stratosphere
	VCSEL	LT	MT	UT	LS				0.04 s (25 Hz)	5% (1 Hz)	3% (1 Hz)	Acc./Prec. need flight, lab verification	Needs flight testing	NSF G-V	Flight tests scheduled for 2007.
	others												Absolute calibration required. Devices may use different spectral lines to access different ranges of humidity – calibration uncertainties		
photo-acoustic			MT	UT	<	S	>								

T = troposphere
S = stratosphere
L/M/U = lower/middle/upper

Remarks of Bruno Neininger:

History: MetAir uses the *meteolabor* (ML) dew point mirror since 1990, and before Bruno Neininger used the prototype since 1979. The LI-7500 replaced a NOAA-IRGA (in service since 1996) in 2003. The LI-6262 is in service since 2001. Both the LI-6262 and the LI-7500 received some modifications, and we apply special operational precautions which we are willing to communicate upon request. An important issue are the scrubbers for CO2 and H2O in both instruments. We recommend exchanging them by actively flushing the diverse compartments.

The ML dew point mirror / fast thermometer was just upgraded by an improved pre-amplifier in order to reduce the noise above 1 Hz. The temperature measurement is now useful up to at least 5 Hz (10 or 20 Hz should be possible), and the dew point is astonishingly parallel with the fast IRGA (LI-7500) up to about 2 Hz (at least 1 Hz). For all the parameters mentioned here we can forward data from the last campaign in April 2007 in Southern France (preliminary now, hopefully quasi-final in June).

4. Recommendations

From this workshop the following recommendations are given in short form:

Instrumentation development: During the workshop a strong deficit of fast humidity instruments was noticed. Therefore it is strongly recommended to enforce development of a replacement of Ly-Alpha instruments (e.g. diode laser technique) and/or development of new source/detector combinations for Lyman-alpha instruments. Sharing the cost of development within EUFAR would be of great benefit for the whole community.

Operators: Improved documentation is recommended including the following items:
Sensor package description, description of data processing and error calculation.
A standardization of data outputs would be desirable.
To achieve a common quality standard within EUFAR an intercomparison of existing calibration methods/facilities should be initiated e.g. by sending around selected reference sensors.
Also more in-flight intercomparisons are necessary to improve quality of data within EUFAR.

Funding: A few very sophisticated humidity calibration facilities exist within Europe (e.g. FZ-Juelich, DLR). To avoid unnecessary and expensive duplication of existing facilities the possibility of funding the access to calibration facilities within EUFAR or other EU projects shall be investigated.
Since the documentation on the website can give only basic information funding for visiting flight facilities in advance is recommended. This would also ease the choice of aircraft and instrumentation.
Funding for in-flight intercomparisons is necessary to improve quality of data within EUFAR.

To support organisation and improve communication within EUFAR it is highly recommended to send EUFAR bureau staff member to EWG meetings!

Users: *Insist* on having gapless documentation about calibration, data processing and error calculations.
The information exchange between operator and user is an iterative process. It is therefore highly recommended for users to contact the operator in early stage of their project.
'Standard' thermodynamic instrumentation is not able to provide reliable air temperature data within heavy water clouds!

? Funding: resources required to maintain calibration documentation etc. ?

APPENDIX

List of participants of the joint EUFAR workshop

Nr.	Name	Email / Telephone	Address
1	Afchine, Armin		Research Centre Juelich Inst. for Stratospheric Chemistry Cloud group 52425 Juelich, Germany
2	Auerswald, Torsten	t.auerswald@tu-bs.de +49.531.391.9987	Technical University of Braun-schweig Institute of Aerospace Systems Hermann-Blenk-Strasse 23 38108 Braunschweig, Germany
3	Bange, Jens	j.bange@tu-bs.de +49.531.391.9973	Technical University of Braun-schweig Institute of Aerospace Systems Hermann-Blenk-Strasse 23 38108 Braunschweig, Germany
4	Bitter, Mark	mark.bitter@tu-bs.de +49.531.391.9818	Technical University of Braun-schweig Institute of Flight Guidance Hermann-Blenk-Straße 27 38108 Braunschweig, Germany
5	Brown, Philip R.A.	phil.brown@metoffice.gov.uk +44.1392.886740	Met Office Cloud Physics Research Fitzroy Road Exeter EX1 3PB, United Kingdom
6	Cremer, Matthias	m.cremer@tu-bs.de +49.531.391.9811	Technical University of Braun-schweig Institute of Flight Guidance Hermann-Blenk-Strasse 27 38108 Braunschweig, Germany
7	Esposito, Marco	m.esposito@isafom.cnr.it +39.0817717325	CNR ISAFoM Via Patacca 85 80056 Ercolano (NA), Italy
8	Fleming, Rex	rfleming@spectrasensors.com +1.303.817.8737	SpectraSensors 927 North Amelia Avenue San Dimas, CA 91773, USA
9	Giez, Andreas	andreas.giez@dlr.de +49.8153.28.2957	German Aerospace Center Flight Facility Oberpfaffenhofen Muenchner Straße 20 82234 Wessling, Germany
10	Hoff, Axel	axel.hoff@dwd.de +49.69.8062.2852 +49.531.25205.28	Deutscher Wetterdienst TI 22 - Messtechnik Kaiserleistrasse 42 63067 Offenbach, Germany
11	Kraemer, Martina	m.kraemer@fz-juelich.de +49.2461.61.3238	Research Centre Juelich Inst. for Stratospheric Chemistry Cloud group 52425 Juelich, Germany
12	Kroonenberg, van den Aline	a.kroonenberg@tu-bs.de	Technical University of Braun-schweig

		+49.531.391.9965	Institute of Aerospace Systems Hermann-Blenk-Strasse 23 38108 Braunschweig, Germany
13	Maser, Rolf	r.maser@enviscope.de +49.69.97840043	Enviscope GmbH Arnoldshainer Str. 5 60489 Frankfurt, Germany
14	Neininger, Bruno	bruno.neininger@metair.ch +41.41.755.38.04	MetAir Sonnenberg 27 6313 Menzingen, Switzerland
15	Quante, Markus	markus.quante@gkss.de +49.4152.872378	Environmental Chemistry Dept. GKSS Research Centre Max-Planck-Straße 1 21502 Geesthacht, Germany
16	Serrano Vargas, Oscar	serranovo@inta.es +34.91.520.16.49	INTA Area de Experimentacion en vuelo y armamento Ctra.Ajalvir Km.4 28850 Torrejon de Ardoz, Madrid Spain
17	Siebert, Holger	siebert@tropos.de +49.341.235.2469 +49.341.235.3424	Leibniz-Institute for Tropospheric Research Permoserstrasse 15 04318 Leipzig, Germany
18	Smit, Herman	h.smit@fz-juelich.de +49.2461.61.3290	Research Centre Juelich ICG-II: Troposphere P.O. Box 1913 52428 Juelich, Germany
19	Zahn, Andreas	andreas.zahn@imk.fzk.de +49.7247.82.2788	Research Centre Karlsruhe Institute of Meteorology and Climate Research (IMK-ASF) Hermann-von-Helmholtz-Platz 1 76344 Eggenstein-Leopoldshafen Germany
20	Zoeger, Martin	martin.zoeger@dlr.de +49.8153.28.1664	German Aerospace Centre Flight Facility Oberpfaffenhofen Muenchner Straße 20 82234 Wessling, Germany
21	Zondlo, Mark	mzondlo@swsciences.com +1.505.984.1322	Southwest Sciences, Inc. 1570 Pacheco Street, Suite E-11 Santa Fe, NM 87505