14.1 INTEGRATION OF HUMIDITY FLUCTUATION SENSORS INTO THE LINDENBERG BOUNDARY LAYER MEASUREMENT FACILITIES: EXPERIENCES, PROBLEMS, AND FUTURE REQUIREMENTS

Ulrich Weisensee*, Frank Beyrich and Jens-Peter Leps,
Meteorological Observatory Lindenberg, German Meteorological Service, Germany

1. INTRODUCTION

A comprehensive boundary layer measurement program has been set up at the Meteorological Observatory Lindenberg (MOL) of the German Meteorological Service (DWD) over the last five years. The measurements are aimed at the investigation of atmosphere - land surface interaction processes over a heterogeneous landscape. Moreover, boundary layer data form an integral part of the "Lindenberg Column", a reference data set created operationally at MOL in order to characterize the vertical structure of the whole troposphere with high vertical and temporal resolution (Neisser et al., 2002).

The experimental boundary layer facilities comprise, i.a., a boundary layer field site (in German: Grenzschichtmessfeld, GM) at Falkenberg - equipped with a 99m tower, various measurement complexes for the determination of air ~, soil ~ and radiation parameters, and a sodar / RASS - and a network of up to seven micrometeorological stations (energy budget measurement network- EBMN) operated over different surfaces in an area of about 20 * 20 km^2 around the MOL site (Weisensee et al., 2001). In addition to a great variety of standard meteorological sensors, these facilities have been equipped with instruments for the operational determination of heat and momentum fluxes continuously throughout the year (profile mast, ultrasonic anemometer-thermometers, laser scintillometer). The operational determination of the latent heat flux based on direct humidity fluctuation measurements, however, is a much more challenging task and has been performed during field experiments only in the past using Ly-α-, Krypton- or infrared hygrometers (Foken et al., 1998).

Current activities are directed towards the integration of different fast-response hygrometers in the existing micrometeorological measurement systems at MOL. In connection with this, a number of problems have to be solved which partially originate from contradictions between operational requirements and sensor characteristics. With respect to long-term operation, the 99m tower and the EBMN both essentially need sensors with low maintenance requirements.

* Corresponding author address: Ulrich Weisensee, Meteorologisches Observatorium Lindenberg, OT Falkenberg, Am Observatorium 12, D-15848 Tauche; email: ulrich.weisensee@dwd.de

Low power consumption of sensors and data acquisition system is especially necessary in the case of the EBMN-stations, which are working battery powered and in a more or less unattended way (maintenance interval up to two weeks).

A RF-based data transmission has been realized in the EBMN to ensure near real-time availability of data and status information. Such a system has usually limited data transmission capacities. Moreover, at each station in the network data from fast-response sensors for flux determination are obtained in addition to standard slow-response sensors. In order to reduce the amount of data which has to be transferred and to obtain a homogeneous data format, the generation and transfer of pre-processed data have been implemented in the EBMN.

A single EBMN-station mainly consists of a number of decentralized data acquisition modules (SYNMET, W.Lambrecht GmbH, Göttingen). In addition to the standard sensors, each of this modules can be equipped with one USA1 ultrasonic anemometer-thermometer (METEK GmbH, Elmshorn) on a serial port. The USA1 provides both raw data (up to 50Hz sampling rate in the current version) and a fully pre-processed data set, which not only includes the wind and temperature information but also a set of turbulence data. A selection of a freely defined subset of this data for storage is possible within the SYNMET-modules. For calculating the values of heat and momentum fluxes for the desired averaging period, we have been using the capabilities of this turbulence data pre-processor.

Additionally, the USA1 provides six analog input channels and two PT100-temperature channels which are sampled synchronously and two counter inputs. In that way, additional fast-response sensors can be integrated. We have been using this besides of integrating inclinometers and accelerometers with the LI7500- Infrared hygrometer (LICOR Inc.) and the KH20- Krypton hygrometer (Campbell Inc.). Both of the hygrometers generated some problems with respect to online turbulence data processing, based on the capabilities of the existing system. The most relevant problems were the internal time delay of the LI7500 and the non linear signal output of the KH20.

Some other issues of importance are the solution of the sensor separation problem, monitoring of long-term stability, sensor re-calibration, application of data correction algorithms and automatic error detection.

2. FAST-RESPONSE HUMIDITY MEASUREMENTS: EXPERIENCES AND PROBLEMS

Sensor Maintenance

The basic instrument for flux measurements, the sonic anemometer, fortunately doesn't need much special maintenance. The only problems we had using the USA1 were spider webs during fall and some data losses in case of transducer icing. In general, the sonics have been working well over several years.
Compared with the sonic, most fast response hygrometers need a lot of special maintenance. Especially Ly-α- and Kr- Hygrometers are relatively sensitive to window scaling. They have to be cleaned not only frequently but also taking into account of the prevailing meteorological conditions. Otherwise a cleaning attempt may even create signal loss instead of signal increase.
The extensive maintenance requirements were the main reason, why we had not performed continuous latent heat flux measurements in the operationally working EBMN during the last years.
Recently, the situation changed with the coming-up of the LI7500 infrared sensor, which seems to fulfil the requirement of reduced maintenance. This sensor seems to be relatively insensitive to difficult environmental conditions. Therefore it will be used at the unattended field stations and at the 99m tower.
Kr- and Ly-α-Hygrometers will be used under regular maintenance, i.e. at the boundary layer field site and during field campaigns.

Time Delay

Sensor separation and (in the case of the LI-7500 hygrometer) a sensor internal time delay result in an asynchronity of the humidity and vertical velocity fluctuation measurements which can not be neglected for flux calculation. This is illustrated in Figure 1

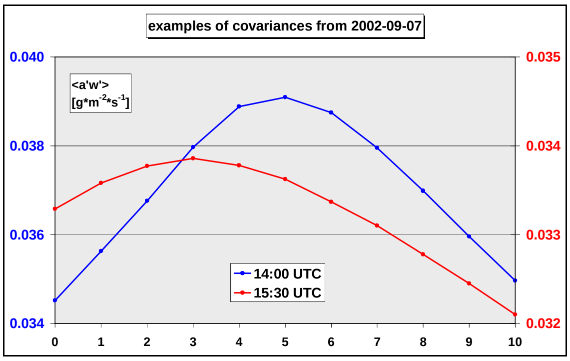

Figure 1
30 minute – averaged covariances between the vertical wind component and absolute humidity, measured with USA1 and LI7500 respectively, as a function of the relative time shift between the original time series (in samples)

There are two general ways to handle this problem. The first is to apply some relative shift of the time series when processing the raw data. This is relatively easy to realize in order to account for a constant sensor-internal time delay but more difficult to implement in order to account for the effect of sensor separation in dependence on wind speed and wind direction. Because of the operational character of the EBMN and the described limitations of data transfer, raw data processing can not be used.
The second option is the application of some correction algorithms to the pre-processed turbulence data (e.g. Moore, 1986).
In order to overcome the time-delay problem in a more technical way we have tested a third method:
In a redesigned version of the Metek-USA1-Sonic, available since summer 2002, it is possible to program an individual time delay for all the analog signal input channels of this device. In that way, constant time delays can be compensated.
In order to compensate the variable time delay due to sensor separation in dependence on wind speed and wind direction, we tried to use a combination between the programmable time delay capabilities and the output data set of the turbulence data processing unit of the USA1. The latter provides i.a. the covariances between the vertical wind velocity and all the analog input channels. In case of connecting the sensor signal of the humidity sensor with a certain number of analog input channels, programmed to different time delays, some kind of hardware correlator is realized.
Using the different calculated covariances for the different time delays, it is possible to determine the maximum of the crosscorrelation function and to calculate the corresponding covariance (Figure 2).

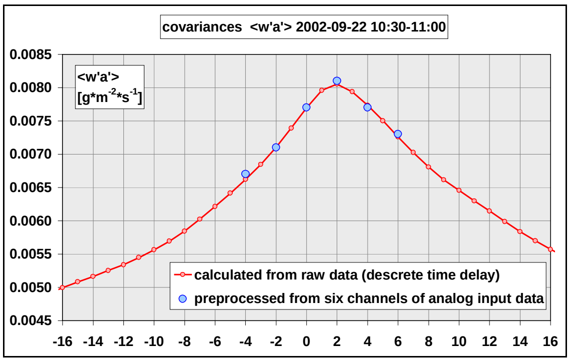

Figure 2
Comparison of covariances calculated from time shifted raw data and from data, processed by the 'hardware correlator'

Choosing an optimum fitting function and peak detection algorithm can be realized with much less meteorological experience than the application of sophisticated correction methods. A detailed evaluation of curve fitting and maximum detection algorithm will be the subject of further studies.

Sensor Signal Conditioning

Unfortunately, not all humidity fluctuation sensors on the market provide a linear output signal. The capability of calculating the logarithm raw input data can not be the main criterion for choosing an optimal data acquisition module for a complex system, in which the flux determination is just one of a number of quite different tasks. Therefore, the Krypton hygrometer will be used at present only at stations with exclusive raw data acquisition and offline data processing. The possible use of a commercial logarithmic amplifier is under investigation.

Transfer Function

Investigation of the transfer function of the sensor and the electronics is sometimes necessary. In case of Kr- and Ly-α- systems, this is partially possible under the assumption, that the transfer function is determined just by the electronics and the influence of the sensor elements can be neglected within the range of interest. Application of some test signals, as usual for transfer function measurements, is possible in principle.
For the IR-systems with their special measuring principle (switching to a reference channel, rotating wheels), application of such a signal is not possible in an easy way. Unfortunately, neither the atmosphere provides a usable test signal. For example, it was impossible for us until now to re-evaluate the LI-7500 internal programmable filter characteristics.
Some tools and descriptions for investigating the transfer function and checking the pulse response, provided by the manufacturer, would be very helpful.

Power Supply

For battery powered stations (EBMN), a minimal power consumption is essential. Krypton- and Lyman-Alpha-hygrometers fulfil this requirement, but can not be used because of the maintenance requirements.
Thus, the relatively high power consumption of the LI-7500 has to be accepted. But, a second problem has to be solved. The high initial current during warm up (more than three times higher than in steady state) generates problems with overload protection circuits of DC/DC-converters. They are detecting the high current values and prevent system working properly. A solution for that problem has not yet been found.

Sensor Calibration

Calibration of the fast, open path absorption hygrometers has been established using some small calibration chamber, either putted into the measuring path (LI-7500) or covering this in the case of Lyman-Alpha- and Krypton-hygrometers.
Generation of a well defined humidity value has been achieved by using LI-610 dew-point generator. Independently of the absorption hygrometer, the humidity is monitored by a precision dew point mirror system (EdgeTech- DewPrime II) additionally.

A procedure of generating a sequence of five defined humidity values first in an increasing and then in a decreasing order has been established. An adjustment time of at least five minutes at every calibration point was found as necessary to achieve stationary and reproducable humidity conditions. Furthermore, the generation of a zero-humidity value (generated with nitrogen) appeared to be valuable.
Since almost six month, we have been performing frequent laboratory calibrations in order to verify the calibration stability. Figure 3 shows the results.

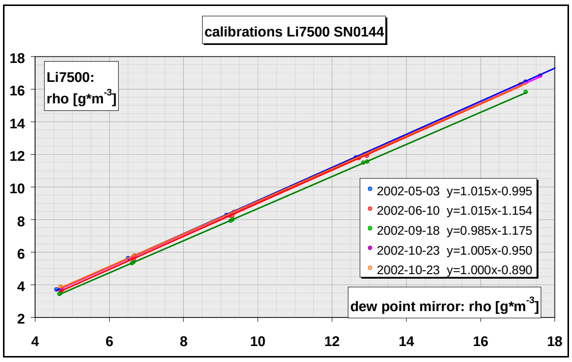

Figure 3: Calibration curves for a LI7500 sensor during a period of six months continuous operation

The calibration functions can be seen as linear and stable with very small differences in general. The reason for the deviation of the third curve still has to be evaluated. The last calibration was performed after replacement of the internal chemicals. No significant deviation had been found for this just as little.

Sensor Comparison

During a field experiment at GM-Falkenberg in May/June 2002, two fast response hygrometers (a LI7500 and a KH20) were compared. Analog data from both sensors were acquired simultaneously with the USA1. The result is shown in figure 4.

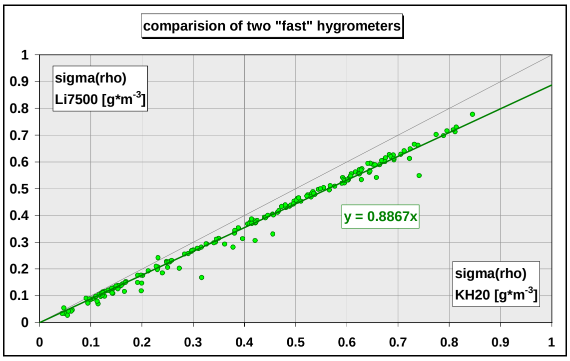

Figure 4: Comparison of 30-minute averages of absolute humidity standard deviation of LI7500 and KH20 over a period of five days.

The standard deviation measured by the KH20 are systematically higher than the standard deviations measured by the LI7500. Reasons for this effect might be the same as for application of the Moore-correction. This has to be evaluated more in detail considering the described difficulties in determination of the sensor transfer functions.
Furthermore, our field-comparisons of the LI7500 measurements with psychrometer and dew point mirror values show a very good agreement for averaged values of absolute humidity except situations with rain or dew. An example for the typical behaviour of the different measuring systems in case of rain (17:40 – 18:00) and dew is shown in figure 5. The IR-system is much less sensitive on this conditions as the Kr-system and provides a higher data availability in case of unattended operation.

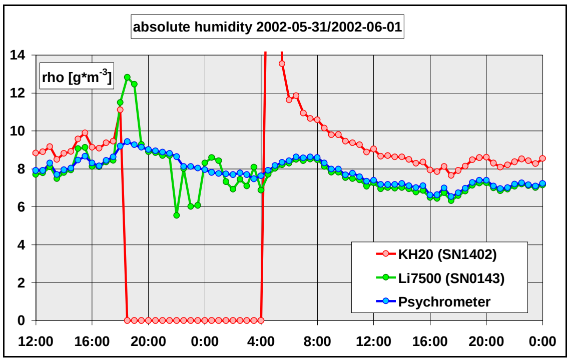

Figure 5: Example of absolute humidity measurements of KH20, LI7500 and Frankenberger Psychrometer

3. NOTES TO THE MANUFACTURERS ATTENTION

The difficulties, discussed before, are not just typical for humidity fluctuation sensors.
It has to be stated, that some kind of little "revolution" has even changed the market of meteorological sensors within the last decade. More and more intelligence is located inside or nearby the sensors itself. Data acquisition changes from analog to digital interfaces. Sensors get a lot of programmable parameters, which can be used to optimize the sensor characteristics for different measuring situations. Network solutions provide the integration of many different sensors, using the same interface.
Unfortunately, all theses changes has generated a number of new problems. Some of them are the "price" for the higher flexibility but some of them could certainly be avoided. At least at the point, where more and more different intelligent sensors have to be integrated in complex, inhomogeneous systems, some kind of standard should be established (as it is usual in industrial branches with many customers). Unfortunately, such a development can not be observed at the meteorological sensor market so far.
This are the reasons for reminding here of some rules, which certainly are well known in the systems developer community but which are not properly taken into account in many cases.
Only a small subset of wishes shall be formulated and directed at the systems developers:

- Try to have a look at your device as an (advanced) sensor, but no longer as a standalone instrument.
- Do not use special hardware and/or software protocols (just one of such a special protocol can kill a whole system concept).
- Report really all programmable parameters within the dataset or within the special answers on parameter request (user can have a different point of view than the developer concerning parameters of more ore less interest).
- Provide linear signal output (not all different types of linearization can be realized in the data acquisition systems, and moreover, linearization is not intended to be done offline in some cases).
- Describe all capabilities, all special features and the working principle of the system as detailed as possible (in other case, really crazy combinations of different sensors or parameters will be realized by the user).
- Take care about system timing (advanced capabilities of time synchronisation will be necessary if network data transfer of decentralized sensors shall be realized).
- Provide all data and status information over all available data interfaces (flexibility in using different interfaces can be the reason for choosing a special sensor, missing parameters at just one of the interfaces can prevent this).
- Do not forget the problem of power consumption (battery operation requires minimal power consumption generally; if DC/DC-converter operation is necessary, high starting currents has to be avoided).

4. REFERENCES

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