FAST-RESPONSE, OPEN PATH OPTICAL HYGROMETER FOR LONG-TERM MEASUREMENTS – EXPERIENCES, RESULTS, FUTURE REQUIREMENTS

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ABSTRACT

After long years of experience with Ly-α- and Krypton-hygrometers for flux measurements in different field campaigns, the fast response, open path optical CO_2/H_2O analyzer LI-7500 has been integrated into the boundary layer measurement facility of the MOL both for flux measurements and for long term monitoring of absolute humidity. The device has been found to be accurate, reliable and stable for relative fluctuation measurements in general with some problems and limitations in detail. Some teething troubles could be overcome with time.
Early devices (S/N before 0283) were found applicable for the determination of absolute humidity as well, so that no additional reference measurement appeared to be necessary for flux calculation. Moreover, reference values for QC purposes of other humidity sensors could be generated from LI-7500 measurements, a great advantage for the design of complex sensor systems and data processing algorithms. Changes in the sensor design by the manufacturer, made in order to fix a problem with CO_2 accuracy, negated the excellent long term specifications with respect to the H_2O measurements of the devices currently sold. After a period of investigation, solutions seem to be in sight to re-approach to the original system specification.

Some of the present device specifics complicate sensor integration into complex measurement systems, which have to be modular, flexible and universal in a multivendor environment.

INTRODUCTION

A comprehensive boundary layer measurement program has been set up at the Meteorological Observatory Lindenberg (MOL) of the German Weather Service (DWD) during the last seven years. The measurements are aimed at the investigation of atmosphere - land surface interaction processes over a heterogeneus land surface.

The experimental boundary layer facilities comprise, i.a., a special 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 micrometeorological stations (energy budget measurement network- EBMN) located in an area of about 20*20 km^2 around the MOL site and operated over different types of land use (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 has been performed during field experiments only in the past using Ly-α-, Krypton- or infrared hygrometers (Foken et al., 1998). A mismatch between operational requirements and sensor characteristics avoided the implementation of the LI7500 as fast response hygrometers into the operationally working systems in the 1990ies.
With the coming-up of a new commercially sold IR- hygrometer, which seemed to be more suitable for continuous, unattended operation at remote stations with low power requirements and infrequent maintenance, we saw the chance for integrating a fast response humidity sensors into these systems. After a test period we introduced the LI7500 first into the Falkenberg- facility in 2002 and later into the EBMN (Weisensee et al., 2003) at different sites.

FAST-RESPONSE, OPEN-PATH- HYGROMETERS

Open path hygrometers (Ly-α- , Krypton- and Infrared- hygrometers) have been used for humidity fluctuation measurements (e.g.: Cerni, 1994), for more than 4 decades.

In case of Ly-α- hygrometers, especially the radiation sources and detectors caused a number of problems. The radiation intensity of the sources was not really stable, sources and detectors were manufactured not commercially (more or less homemade, some changes in manufacturing over the years, loss of experience), and they were very expensive. Moreover their lifetime was strongly limited.

Krypton radiation sources were not so delicate as Ly-α- sources, but the manufacturing dilemma and the price were problems as well. Due to the spectral characteristics the measurements were more sensitive to Oxygen. This requires a special oxygen correction, based on additional pressure measurement.
Both, the Ly-α- and the Krypton- hygrometer use a special window material (magnesium fluoride), which passes the far UV radiation. This material changes its transfer characteristics in humid environments by interaction of atmospheric constituents with UV photons. Windows had to be cleaned manually more or less frequent. Besides this maintenance requirements, both sensor types need accurate reference measurements of mean values of temperature and humidity as a reference.
Another disadvantage is the wide range, nonlinear output signal of both systems. This either requires special analog signal processing or the use of wide range A/D-converters for accurate calculations.
Some important advantages of both sensor types shall not be withheld. The compact sensor design, the small disturbance of wind field, the path length of a few millimeters only and the high bandwidth make the systems preferable for flux measurements, especially close to the ground. Furthermore, the low power consumption can be very advantageous in case of battery powered measuring stations.

The Lindenberg group has a long experience in using such hygrometers (Foken et al., 1998). Different types of hygrometers were used (L-5V Buck Research ,KH20 Campbell, KOH20 Mierij Meteo), mainly during a number of field experiments over time periods not exceeding a few weeks.

Due to the special sensor characteristics and maintenance requirements in combination with some external conditions, such hygrometers were not suitable for integration into operational, more or less unattendedly working measuring facilities.

Hygrometers, using the absorption in the IR region of the spectrum, had been constructed since the early seventies of the last century. The most important advantage of these systems was that most of the stability and lifetime problems of UV- hygrometers didn't occur. IR- hygrometers have the capability to act as an absolute measuring instrument due to the physical properties of the differential absorption principle. Not all systems reach this well due to imperfect electronic or optical characteristics. Most of the IR- hygrometer were more or less special constructions, which comprise the particular interests of the developing institution. Optical path length, flow distortion by sensor geometry, power consumption, special interfaces, temperature range and accuracy were points of discussion which over the years prevented the broad use of such a hygrometer in our long-term monitoring programs.

LICOR LI-7500 Open Path CO_2/H_2O Analyzer

The situation seemed change with the coming-up of a modern infrared sensor, the LICOR LI-7500 Open Path CO_2/H_2O Analyzer at the end of 1999. At first glance, this system seemed to fulfill most of our current requirements:

- small sensor geometry for minimum flow distortion (diameter 6.5cm, length 30cm, weight 0.75 kg)
- path length comparable with that of modern sonic anemometers (12 cm)
- outdoor capability of all system components (head, control box and cables)
- low power consumption for battery powered stations (10.5 .. 16VDC, <10W after initial warm up)
- high precision
- absolute measurements
- analog and serial high speed interfaces (RS232 (20Hz), SDM (40Hz), 2x DAC16 (300Hz updated))
- additional analog inputs (2 channels for temperature and voltage)

Based on this, we decided to integrate this type of devices into our EBMN (Weisensee et al., 2003) for continuous flux measurements.

The system specifications (a subset of which is given in table 1) promised both accurate fluctuation measurements and the determination of precise mean values of absolute humidity with one and the same sensor. This should allow to work without a second independent (slow-response) hygrometer for providing reference humidity data, and hence to avoid calculations based on sensors with different characteristics. It should give the opportunity to use the absolute humidity measurements for QC purposes (independent comparison data) of standard humidity sensors (Polymer sensors, Psychrometer). All of theses different sensors have their own advantages and disadvantages. Some of them do have linearity problems, some require considerable maintenance, some of them don't work under specific conditions. But in combination, they will be able to generate an accurate data set over the whole year under a great variety of weather conditions.

Figure 1: LI-7500 sensor head

Figure 2: field installation (LI-7500, USA1)

	LI – 7500 original specification (S/N < 0283)	VTP6-CU (dew point mirror)	LI – 7500 revised specification (S/N 0283 and higher)
calibration range / measurement range	0 – 42 g/m^3	-50 .. 50 °C (air temperature) -65 .. 50 °C (dew point temp.) 40K (max. depression at 20°C)	0 – 42 g/m^3
zero drift with temperature max. (per °C) typ.	± 0.01 g/m^3 ± 0.003 g/m^3		± 0.04 g/m^3 ± 0.02 g/m^3
accuracy of temperature measurement		± 0.15 K (-20 .. 50 °C) ± 0.25 K (-65 .. -20 °C)	
derived accuracy of absolute max. humidity measurements typ.	± 0.750 g/m^3 (-25..50°C) ± 0.225 g/m^3 (-25..50°C)		± 3.0 g/m^3 (-25..50°C) ± 1.5 g/m^3 (-25..50°C)
accuracy of absolute humidity measurements at different air temperatures		ca. ± 0.6g/m^3 (50°C) ca. ± 0.2g/m^3 (25°C)	

Table 1: Selected specifications of the LI7500 for the humidity measurement (at 25°C and 980hPa) before and after the "solar fix" and of a dew point mirror system (VTP6) for comparison.

The accuracy of absolute humidity measurements, derived from the original system specifications given in Table 1, is comparable to the accuracy of typical dew point mirror systems for outdoor use. In conjunction with the LI-7500 data sheet statements "...Accurately measures absolute densities..." and "...Absolute ... gas analyzer ..." it could be expected, that an alternative system to large, heavy weight, power intensive dew point mirror systems was found.

USE OF LI-7500 AT MOL

Since the end of 2000 when we bought the first two systems we have been using six LI-7500 systems. After system tests, the implementation of a sensor calibration procedure and some sensor comparisons, we realized two field experiments in 2002, including humidity fluctuations measurement as an essential part (Mauder et al., 2005).

Since the beginning of 2003, LI-7500 systems have been integrated into the different operationally working EBS- stations based on the analog coupling of the IR- hygrometer and a sonic anemometer, using the sonics capability to provide a pre-processed turbulence data set which contains all terms necessary for flux calculations. In case of GM located EBS, the acquisition of raw data was realized in parallel and it was temporarily used for special investigations. In May and June 2003 the complex field experiment LITFASS 2003 (Beyrich et al., 2004) took place at MOL. LI-7500 measurements were part of the measurement program, partially based on the operational version of the EBMN.

Quite a lot of experience could be accumulated over the years. Different problems could be solved, but, unfortunately, a number of problems still has to be solved in the future.

Some of these experiences shall be described in the following section.

EXPERIENCES IN USE OF LI-7500

Sensor Calibration

Calibration of the fast-response, open path absorption hygrometers has been established at MOL using some small calibration chamber, which is either put into the measuring path (LI-7500) or covers this in the case of Lyman-α- and Krypton-hygrometers.
Generation of a well defined humidity value is achieved by using an 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.
An automatic calibration procedure has been established. It covers a number of pre-defined humidity values, which are generated sequentially, first in an increasing and then in a decreasing order. An adjustment time of at least seven minutes at every calibration point was found necessary to achieve stationary and reproducible humidity conditions.
During the last years, we have been performing frequent laboratory calibrations of several of our LI-7500 sensors in order to verify their calibration stability.
Under laboratory conditions, the calibration equation of the LI-7500 were found to be linear and stable in time with very small differences in general.
Some calibration was performed after replacement of the internal chemicals. No significant deviation from previous calibrations was found.

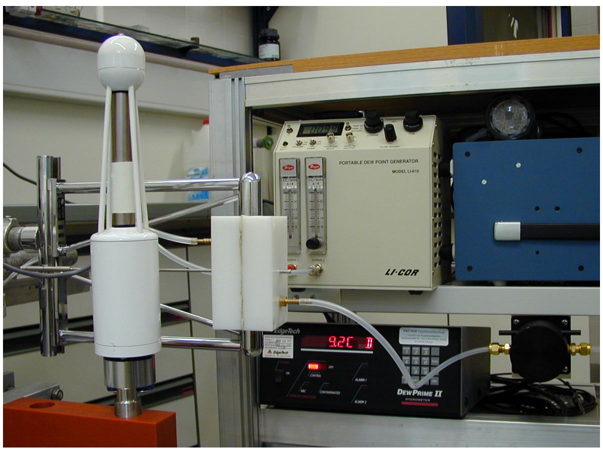

Figure 3: Calibration facility for open path hygrometers

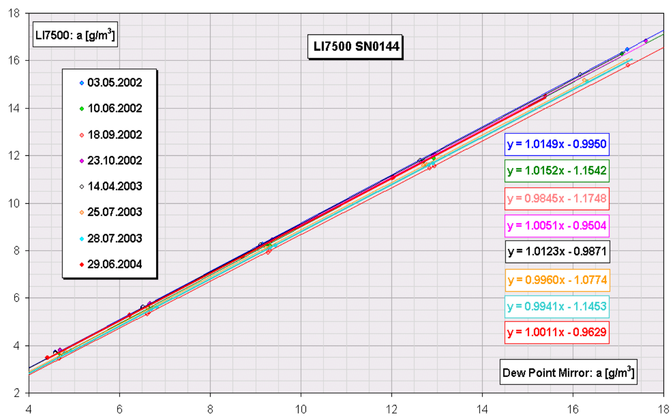

Figure 4: Result of repeated laboratory calibrations of a LI-7500 sensor over a period of two years

Measurement Restrictions

Of course, an open path system is relatively sensitive to any disturbance within the measuring path like rain, snow, dew, ice, fog, insects. This applies to the LI-7500 as well. But, in general, the LI-7500 is less sensitive to these conditions than the Ly-α- and Krypton- sensors. Nevertheless, the data availability especially during winter is not yet satisfying.
From our point of view, it could be increased noticeably by implementing a window heating or a small air flushing.

Diagnostic Information

The LI-7500 provides some diagnostic information, which only consists of a 1 byte unsigned integer. It contains information about the chopper temperature controller, the status of the chopper motor, the detector cooler and the synchronization between the embedded software, the digital signal processor and the chopper motor. This information is encoded in the highest 4 bit of the diagnostic byte. Additional information, the so called AGC- value is encoded in the lower half byte. This AGC value indicates the cleanness of the window. The bits are representing the AGC value range from 0 .. 100% in steps of 6.25%. Manufacturer tells typical clean window values of 55-65%. Higher values shall indicate the necessity to clean the windows.
So, in fact, the information is available just with a resolution of 7 steps in maximum.

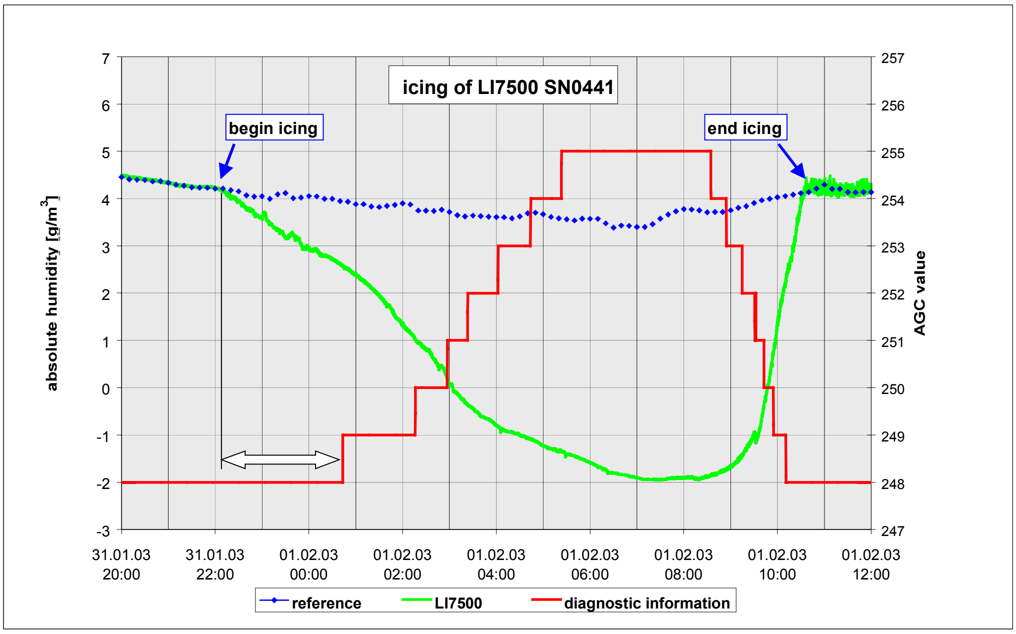

Figure 5: Diagnostic information, given by the LI-7500, during a period of sensor icing

As it can be seen in figure 5, the AGC value could be used for the QC of the data . The gradual decrease of the output absolute humidity value results from a loss of signal due to rime on the window which is indicated by the stepwise increment of the status signal. But information is not provided with the required resolution. A time period of about 3 hours with icing remains undetected in the example.
Furthermore, it is impossible to get out this diagnostic information via the analog interface, which is seen as a serious disadvantage. On the one hand, this reduces the flexibility for using the system in different measuring environments, and on the other hand, an analog AGC- output could be very helpful in realizing an automatic window cleaning device.
Unfortunately, the manufacturer does not provide a high-resolution diagnostic information over all interfaces so far.

Delay Time

Data acquisition and processing processes within the LI-7500 need a certain time. LI-7500 has a fixed throughput delay of originally 230 ms. It can be increased by the user in a limited number of 6 ms steps (see LI-7500 manual) up to about 300ms.
This shall provide the possibility to minimize the time shift between different sensors when coupling the LI-7500 with e.g. a sonic.
This time delay between the concentration measurement and the vertical wind measurement is not negligible in case of flux measurements, on contrary, it can generate quite a large error. This error depends on wind speed and wind direction. System immanent time delays can generate additional errors. Users tend to reduce the latter as far as possible.
The best way to eliminate this error generally is to acquire raw data, performing a shift between the time series and find the maximum cross correlation.
Assuming that all system delays of the combined measurements are well known, the user can reduce the fixed time delay error by compensating it trough the online application of an additional time delay between the different input channels. Unfortunately, not so many data acquisition systems on the market provide such a possibility. As described in the introduction, acquisition and processing of raw data is not possible in all our applications.
Flux measurements at the Energy Balance Stations are performed using a USA1 ultrasonic anemometer-thermometer (METEK GmbH, Elmshorn). USA1 allows the synchronous sampling of analog input channels which we used to acquire the LI-7500 analog output signals. Furthermore it includes a turbulence data processor which provides a complete turbulence data set.
In a redesigned version of the Metek-USA1-Sonic, initiated by DWD and available since summer 2002, it has been possible to program an individual time delay for all the analog signal input channels of this device. In this way, constant time delays can be compensated. In addition to that, we tried to implement a kind of hardware correlator for the compensation of variable time delays.

In the middle of 2003, LI-COR company published an information on a software bug in all firmware versions before that date. Timing information, given in the manuals, had been found incorrect and not constant. Consequently, post operational correction of calculated flux data gathered before that time was possible only if raw data time series are available.
Completely new values of time delay were given in connection with a new firmware revision. Unfortunately, there are different values for DAC- and RS232/SDM- output. This further reduces the compatibility and flexibility and increases the risk of configuration errors.
This example illustrates the relevance of apparently small technical problems. The only way to avoid such problems and to become independent from manufacturers choice which pre-processed data could be of users interest seems to be the acquisition of raw data. Hopefully, the technical development soon provides this possibility even for autonomously working, battery powered stations with limited data transfer capacity.

Direct Sunlight Sensitivity

In Mai 2002, the German representative informed about a new LI-COR note, published in February 2002, announcing the recognition of a large sensitivity of the CO_2- measurements to direct sunlight found for some devices.
LI-COR described a simple test to determine, whether or not a device is affected. An ad hoc procedure was suggested to reduce the effect (tilted mounting) and the manufacturer offered the possibility to send back affected devices for repair.
So far so good! Unfortunately, the manufacturer modified the LI-7500 to avoid the direct sunlight sensitivity in a way, such the system specification changed dramatically as described in the next section.

Temperature Sensitivity

The temperature sensitivity specification of the original LI-7500 design is given in Table 1. In order to solve the sunlight sensitivity problem, the manufacturer changed the optical filter combination in 2002 (S/N 0238 and higher). CO_2- specification didn't change, but H_2O- specification changed dramatically (see Table 1 – revised specification) as a result of this sensor modification. Especially the parameter "Zero drift with temperature" increased. Furthermore, the cross sensitivity to CO_2 increased.
In consequence, LI-7500 with solar fix changes are no longer suitable for absolute humidity measurements. This effect doesn't affect the usability of the LI-7500 for flux measurements.

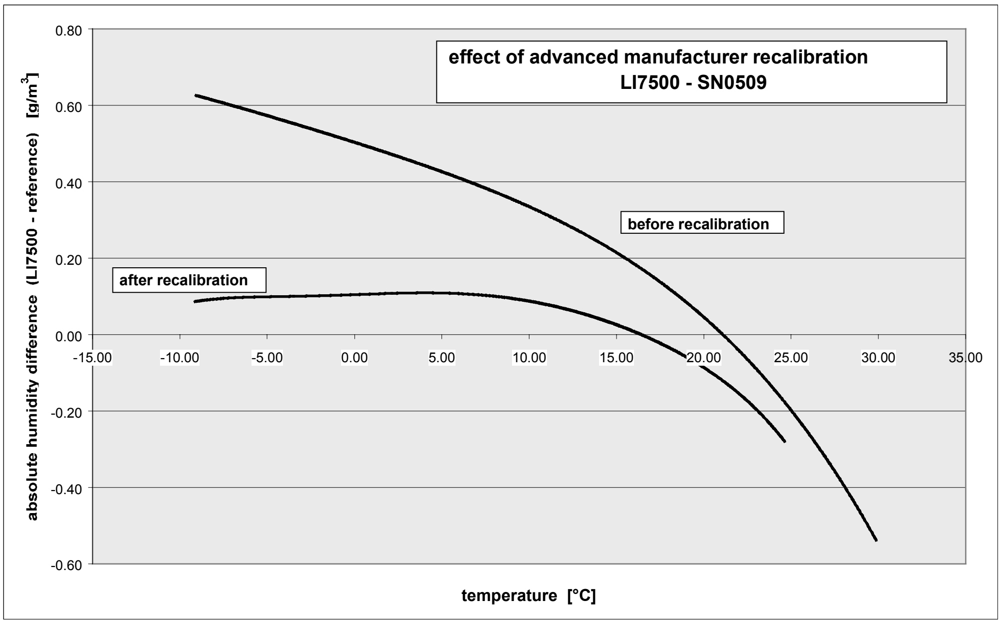

Figure 6: Effect of an advanced re-calibration of a LI-7500 (preliminary result, just for a part of the whole temperature range and just for absolute humidity values between 1 .. 3 g/m^3)

An experimental re-calibration of two LI-7500 sensors was performed by the manufacturer in August 2002 in the LI-COR laboratory to achieve the original H_2O-specification. A result of laboratory measurements, based on a re-calibrated sensor, can be seen in Figure 6. The first impression is, that the temperature drift significantly decreases, especially in the region of lower temperatures. For evaluation of the re-calibration effect further field measurements have to be performed, covering the whole operational temperature range and including all expected values of absolute humidity.
Nevertheless, the best way seems to eliminate the reasons for the temperature drift.

Output Values

As mentioned in the section "diagnostic information", the AGC value would be very helpful as an analog output. Especially in conjunction with the problem of evaluating the temperature sensitivity, providing the original values of absorption at the different wavelength via the output data set would be of special interest. Currently, there are only two derived output values for CO_2-absorption and for H_2O-absorption. Both include a full calculation of cross correlation and zero drift.
Unfortunately, the composite of the output data set differs depending on the used interface (DAC, RS232, SDM). It seems to be, that some values are calculated only in the PC software. But this is not described anywhere.

PC Communication Software

The LI-7500 PC Communication Software is used to transfer data and configuration files between the analyzer and the PC. It gives the possibility to edit different system parameters, to display measured data and to store data to disk. Unfortunately, not all values can be displayed (e.g. AGC) on the implemented strip chart. Any inconsistencies exist, depending on the software version. Care must be taken in case of device configuration.

Power Supply

For battery powered stations (EBMN), a minimum power consumption is essential. The higher power consumption of the LI-7500, in comparison to Krypton- and Ly-α- hygrometers, has to be accepted. A real problem is the high initial current during warm up (more than three times higher than in steady state). It generates problems with overload protection circuits of DC/DC-converters. They are detecting the high current values and prevent the system working properly. This has to be kept in mind in the phase of system design. Electronic boxes with S/N 0370 and higher shall have a slightly different design, which shall give a smaller initial current. This effect is not really significant and doesn't solve the problem in general.

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