UNIVERSITÄT BAYREUTH

Abt. Mikrometeorologie

Documentation and Instruction Manual for the Krypton Hygrometer Calibration Instrument

In cooperation with

Gesellschaft für Akustik und Fahrzeugmesswesen mbH, Zwickau

Thomas Foken

Hubert Falke

Arbeitsergebnisse
Nr. 42 (update)
Bayreuth, January 2010 (update December 2011)

Arbeitsergebnisse, Universität Bayreuth, Abt. Mikrometeorologie, Print, ISSN 1614-8916
Arbeitsergebnisse, Universität Bayreuth, Abt. Mikrometeorologie, Internet, ISSN 1614-8924
http://www.bayceer.uni-bayreuth.de/mm/

Eigenverlag: Universität Bayreuth, Abt. Mikrometeorologie
Vervielfältigung: Druckerei der Universität Bayreuth
Herausgeber: Prof. Dr. Thomas Foken

Universität Bayreuth, Abteilung Mikrometeorologie
D-95440 Bayreuth

Content

1 Introduction

Fast response hygrometers are nowadays an important part of all measuring complexes for turbulent energy fluxes. There has been a significant change in the measuring systems within the last 10-15 years. While in the 90s of the previous century mainly UV absorption lines were used in commercially available sensors (Foken *et al.* 1995),at present sensors working in the IR absorption lines are almost exclusively used. The reason is that the hydrogen lamp for hygrometers working at the Lyman-alpha line of 121.56 nm is not very stable and the lamps were mainly handmade. On the other hand the sensitivity of IR-sensors has been increased and while these sensors have been commercially available since the 90s, the first instrument developments are dated 30 years earlier (for overview see Foken *et al.* 1995).

The Lyman-alpha hygrometer was developed at the beginning of the 70s almost in parallel in the USA, the Soviet Union and the former GDR (Buck 1973; Kretschmer and Karpovitsch 1973; Martini *et al.* 1973) and the American instrument was commercially produced by AIR Inc., Boulder CO. About ten years later a second type of UV hygrometer was developed using a krypton lamp (Campbell and Tanner 1985). The benefits of this instrument were a longer lifetime and easier production. But the absorption band is not directly located in the Lyman-alpha band and has a cross sensitivity to oxygen (see Chapter 2).

All these hygrometer types work on the basis of Lambert-Beer's law

$$I = I_0 \exp\left(-\rho_w k x\right) \tag{1}$$

with the current at the receiver I and of the lamp I_0, the absolute humidity ρ_w, the absorption coefficient k and the path length between lamp and receiver x. While emission and detection efficiencies affect I_0, these do not affect flux measurements since only the fluctuation level needs to be determined. However, knowledge of k and x is required for proper scaling of fluctuations in ρ_w.

The calibration procedure has usually been carried out for different absolute humidities at fixed path lengths. Because the hydrogen and the krypton lamps are not very stable in time and the calibrations in a moisture chamber are not very useful during field campaigns, the calibration with variable path length was developed. According to Eq. (1) the calibration is also possible by a changing path length in the case of a constant absolute humidity. A first Lyman-alpha hygrometer with variable path length was proposed by Buck (1976) and an updated version by Foken et al. (1998). A simple application of this system to the krypton hygrometer is impossible, because this device works with two absorption lines, each with two absorbers. Nevertheless, such a development is necessary because IR hygrometers are not very sensitive in measuring absolute humidities below 2-4 g m^{-3}, and in this range the calibration is not very linear unless a special calibration for these conditions is applied, which is – under complicated environmental conditions – difficult to realize. But such low humidities are typical in cold regions and at high altitudes. Therefore a calibration system with variable path length for krypton hygrometers was developed by the University of Bayreuth, Department of Micrometeorology, in cooperation with the Gesellschaft für Akustik und Fahrzeugmesswesen mbH, Zwickau who manufactured already the software and controller for the calibration system of the Lyman-alpha hygrometer and the prototypes of the proposed device.

2 Theory of the Krypton-Hygrometer and the Calibration Instrument

2.1 Characteristics of the krypton lamp

The source of the krypton hygrometer KH20 is a low-pressure krypton glow tube. Emission from the krypton tube exhibits a minor band at 116.49 nm (band 1) and a major band at 123.58 nm (band 2). Radiation at 123.58 nm is strongly attenuated by water vapour whereas absorption by other gases in the optical path is relatively weak at this wavelength. Radiation at the shorter wavelength (116.49 nm) is attenuated by water vapour and also by oxygen molecules, but the intensity of the transmitted beam is considerably reduced at this wavelength by magnesium fluoride windows fitted to the source and detector tubes(Campbell and Tanner 1985).The spectrum of the krypton lamp is shown in Fig. 1.

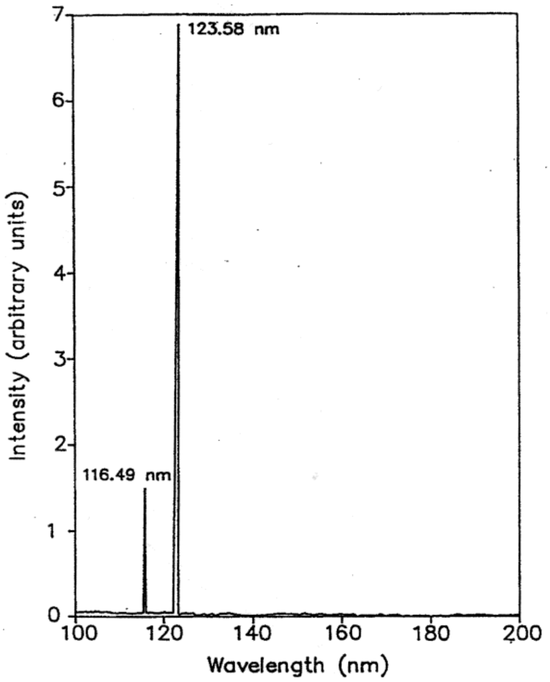


Figure 1: Spectrum of the krypton lamp (Campbell and Tanner 1985, courtesy Scientific Services, Rocky Hill, NJ)

Therefore the output signal depends on both path lengths and both absorbers: water vapour and oxygen (Buck 1976; Campbell and Tanner 1985)

$$I = I_{01} \exp\left[-x\left(k_{w1}\rho_{w1} + k_{O1}\rho_{O1}\right)\right] + I_{02} \exp\left[-x\left(k_{w2}\rho_{w2} + k_{O2}\rho_{O2}\right)\right] \qquad (2)$$

where the indices 1 and 2 refer to the path length for 116.49 nm and 123.58 nm, respectively, and the indices w and o for water vapour and oxygen.

According to Tillman (1965) the absorption coefficient in the short wavelength is half of that in the long wavelength.. Because of this,and that only the signal of these two wavelengths is measured, it is possible to combine both water vapour absorptions. For the oxygen absorption the fraction of band 1 is *f* and of band 2 is (1-*f*). The simplified Eq. (2) is

$$I = I_0 \exp\left(-xk_w\rho_w\right)\left[f \exp\left(-xk_{O1}\rho_{O1}\right) + \left(1-f\right)\exp\left(-xk_{O2}\rho_{O2}\right)\right] \qquad (3)$$

For most applications the additional oxygen absorption can be ignored and the basic equation for the calibration of the Campbell Sci. krypton hygrometer KH20 is

$$\ln(V) = \ln(V0) - a \cdot X \cdot Kw \tag{4}$$

with the constant *V0* in ln (mV), approximately 8...10 ln(mV), the intercept exp(ln V0) in mV, the calibration coefficient (effective absorption coefficient for water vapour) *Kw* in ln(mV) m^3 g^{-1} cm^{-1}, the coefficient *XKw* in ln(mV) m^3 g^{-1} for a given path length *X* in cm and the absolute humidity *a* in g m^{-3}.

This simplification is possible because only the measurement of the fluctuations is of interest. If the oxygen concentration does not change (for nearly constant air pressure) this calibration can be used. Nevertheless small corrections are recommended (Tanner *et al.* 1993; van Dijk *et al.* 2003).

2.2 Calibration with variable path length

Since a change in the output signal can be produced by either a change in humidity and oxygenor a change in path length, it is possible to alter the path length for nearly constant humidity and oxygen conditions in order to simulate a change in humidity or oxygen. This makes a calibration with a variable path length for constant humidity possible for the Lyman-alpha-hygrometer (Foken *et al.* 1998), because the ratio of the absorption coefficients is about $2 \cdot 10^3$(Tillman 1965), while the ratio of the densities is typically about $2 \cdot 10^{-1}$ and therefore the effect of the water vapour is 100fold higher than that of the oxygen.

This is not the case for the krypton hygrometer, where the absorption coefficients of the water vapour and the oxygen are in the same order by an at least twentyfold higher partial density of oxygen. The absorption coefficient for water vapour used in the krypton hygrometer papers were referred to Watanabe and Zelikoff (1953) and Johns (1965). According to the more recent paper by Mota et al.(2005)[1] with data of a spectral solution of 0.05 nm, with the transformation from base e to base 10 (Finlayson-Pitts and Pitts 2000), it follows for band 1k_{w1}=28.5(atm at 298 K)$^{-1}$cm^{-1} and for band 2k_{w2}=49.5(atm at 298 K)$^{-1}$cm^{-1}.Ogawa and Ogawa (1975)[1] reported about absorption coefficients for oxygen with a spectral resolution of about 0.1 nm. According to this study the oxygen absorption coefficient in band 1 is k_{o1}= 19.9(atm at 298 K)$^{-1}$ cm^{-1}(nearly identical with the water vapour absorption) and for band 2:k_{o2}= 32.5(atm at 298 K)$^{-1}$ cm^{-1}, less than one tenth of the water vapour absorption. Furthermore the signal of band 1 is less than 20 % lower than those of band 2 because of the lower intensity (Fig. 1) and the smaller width of the band. Furthermore in this spectral range the absorption maximum of ozone with about k_{o31}≈83 (atm at 298 K)$^{-1}$ cm^{-1} and k_{o32}≈170 (atm at 298 K)$^{-1}$ cm^{-1}is based on a spectral resolution of about 0.6 to 0.8 nm (Ackerman 1971)[1], but the ozone concentration is many times lower than the oxygen and water vapour concentrations.

$$I = I_0 \exp\left\{ -x\left[\frac{f}{1-f}\left(k_{w1}\rho_{w1} + k_{O1}\rho_{O1}\right) + k_{w2}\rho_{w2} + k_{O2}\rho_{O2} \right]\right\} \tag{5}$$

The absorption coefficient in both bands is approximately 2fold higher for water vapour but the density is at least twentyfold lower and the effect of band 1 is much smaller than of band 2.The

---

[1] Data from “MPI-Mainz-UV-VIS Spectral Atlas of Gaseous Molecules” (http://www.atmosphere.mpg.de/enid/2295)

most significant absorption is in band 2 due to oxygen and Eq. (5) can be written is the following form

$$I = I_0 \exp\left(-x k_O \rho_O\right) \tag{6}$$

by accepting an error of the calibration of about 10 %, which can be reduced for calibrations in different humidity classes. The calibration procedure with variable path length is based on the following assumptions:

- The calibration coefficient can be determined by variation of the path length with constant gas concentrations.
- The intensity of the krypton lamp has the same influence on the water vapour absorption and on the oxygen absorption; therefore it is possible to use oxygen for the determination of the calibration of the lamp for the case when the oxygen absorption is much larger than the water vapour absorption due to the higher density.
- If a humidity calibration of the krypton hygrometer (e.g. from the producer) and an oxygen calibration (with the calibration instrument with variable path length) are available for the same time, the calibration coefficient during the lifetime of the krypton hygrometer can be controlled by the oxygen calibration alone.

According to Eq. (4) it follows for the oxygen calibration that

$$\ln(V) = \ln(V0) - \rho_O \cdot x \cdot K_O \tag{7}$$

By comparison of the coefficient K_O of the oxygen calibration with those of the first oxygen calibration (for which also a humidity calibration is available) the coefficient of the humidity calibration K_w can be corrected. Because of the cross-sensitivity to humidity of the oxygen calibration the error is less than 10 %, which is much lower than the change of the intensity of the krypton lamp within one year.

Finally, with the calibration coefficient for oxygen K_O and its change with time, the change of the calibration coefficient for water vapour K_w can also be recalculated. It is important that for a new instrument the water vapour calibration from Campbell Sci. and an oxygen calibration performed with the described calibration instrument are available. Otherwise a water vapour calibration for constant oxygen concentration must be repeated.

According to Tanner et al. (1993) the effect of oxygen fluctuations due to pressure fluctuations is nearly negligible in comparison to the water vapour fluctuation. Therefore the oxygen absorption is not relevant for flux measurements. Nevertheless a small Bowen-ratio dependent correction is necessary (Tanner *et al.* 1993; van Dijk *et al.* 2003).

2.3 Calibration procedure

The calibration procedure follows the calibration protocol of the krypton hygrometer KH20 by Campbell Sci. But instead of different absolute humidities the path length is changed. The output signal must be measured for about 15-20 different path lengths in order to receive a sufficient number of calibration points. It is assumed that the most exact points of the calibration are in the centre of the used range of calibration. The regression according to Eq. (7) starts with a minimum of 5 measuring points [ln V, X] for a given absolute humidity. Measuring points will be added to the regression as long as the linearity is given according to the test parameters of the calibration given in

Table 1. There are two calibration modes: indoor and outdoor calibration.The indoor calibration using typical outdoor conditions is recommended. It is strongly recommended to perform the outdoor calibration under moderate turbulent conditions in the morning or late afternoon hours. If the regression is not well correlated or is not linear, the calibration must be repeated. An example of a regression is shown in Fig. 2.

Table 1: Regression settings

regression setting	laboratory calibration	outdoor calibration
minimum permitted correlation coefficient	0.995	0.990
maximum permitted difference of data from the regression line in ln(mV)	0.1	0.2
Allowed deviation of the calibration coefficient from the calibration before in %/100	0.05	0.1

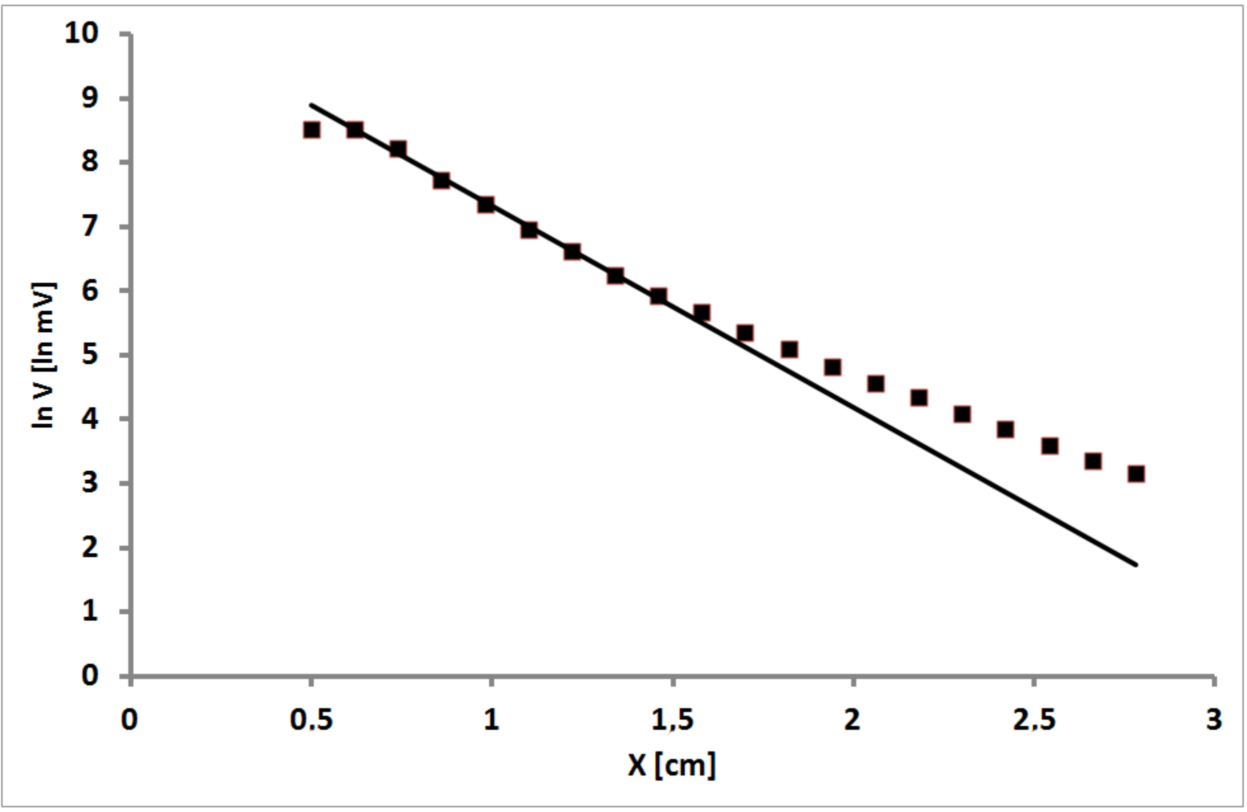


Fig. 2: Example of a calibration diagram with the measuring points (squares) in relation to the path length *X*, device KH20 No. 1649, Zwickau 14.07.2011, $\rho_W = 7.8$ g m^{-3}, $\rho_O = 241$ g m^{-3}

With the water vapour and oxygen calibration for a new instrument the determined oxygen calibration will be re-calculated into a water vapour calibration. Furthermore the programme compares the calibration with the previous calibration of the same device. If the calibration is within 5 or 10 % of the chosen path-length or optimal path length, both calibrations differ only within typical errors and no change of the calibration coefficient is necessary.

The results of the calibration are the parameters for a given measuring path length X [cm]: constant V_0 in [ln (mV)]¸ coefficient K_O in [ln(mV) m^3 g^{-1} cm^{-1}],, and the coefficient XK_O in [ln(mV) m^3 g^{-1}] is also given.

The optimal path length is in the centre of the linear calibration range. This parameter should help to inform the researcher as to whether the chosen path length was optimal according to the operational environment.

Finally with the calibration coefficient for oxygen K_O and its change within the time also the change of the calibration coefficient for water vapour K_w can be recalculated. It is important that for a new instrument the water vapour calibration from Campbell Sci. and for the new instrument an oxygen calibration with the described instrument are available. Otherwise a water vapour calibration for constant oxygen concentration must be repeated.

The new calibration coefficient can be calculated with the relation

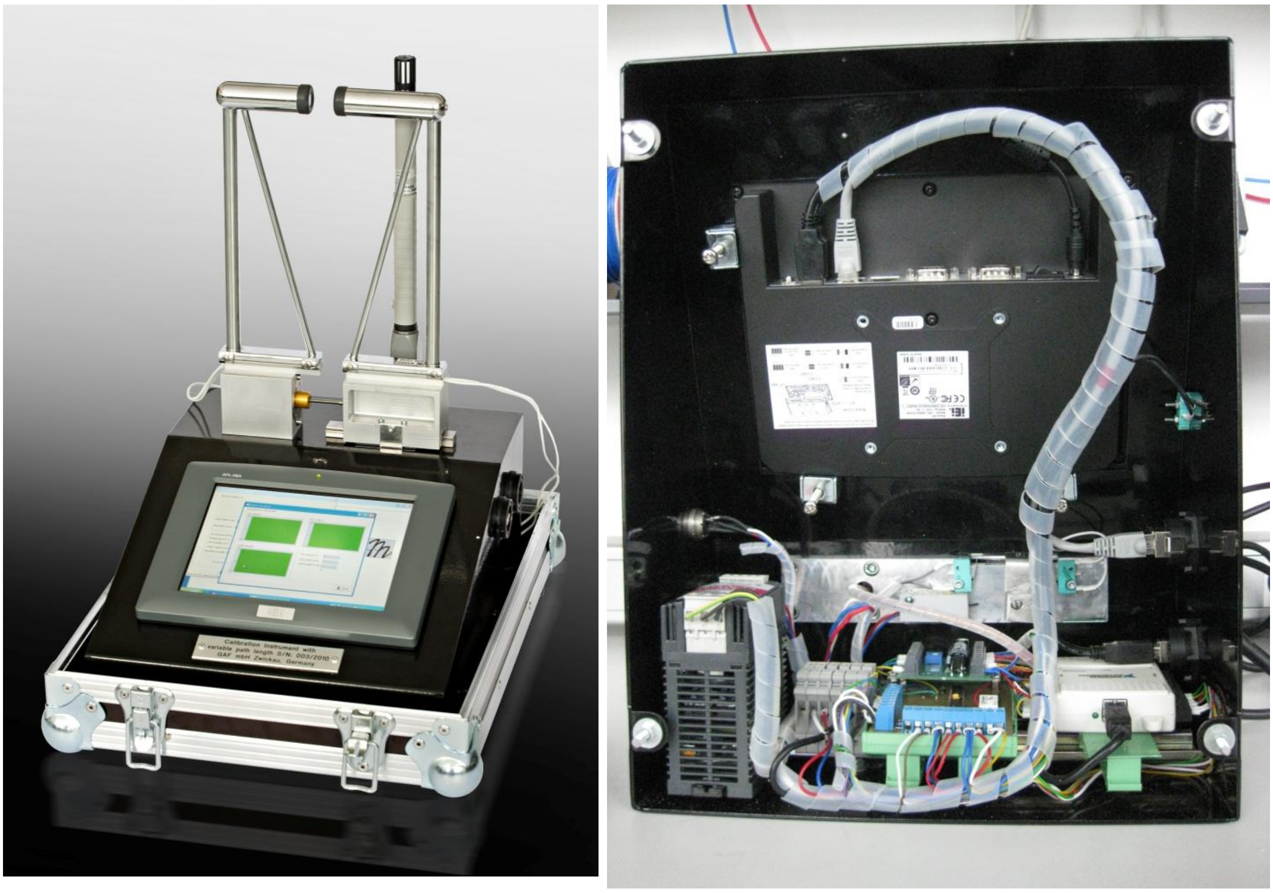
$$K_{w-new} = K_{w-old} \frac{K_{O-new}}{K_{O-old}} \tag{8}$$

Remark: In the case of the first oxygen calibration for $K_{O\text{-}old}$ only the calculated K_O value should be used.

The Campbell Sci. calibration protocol includes calibrations for clean and scaled windows and different ranges of the humidity. All Campbell devices are probably calibrated at an altitude of more than 1000 m a.s.l. with a lower oxygen concentration than that used in most regions of the world. Therefore a control of the influence of the oxygen concentration and the conditions of the windows are necessary. With the in-situ calibration (calibration with variable path length) this problem can be ignored, but the calibration can then only be used for the calibration site and must be repeated if the device is used under different conditions or if the windows are scaled.

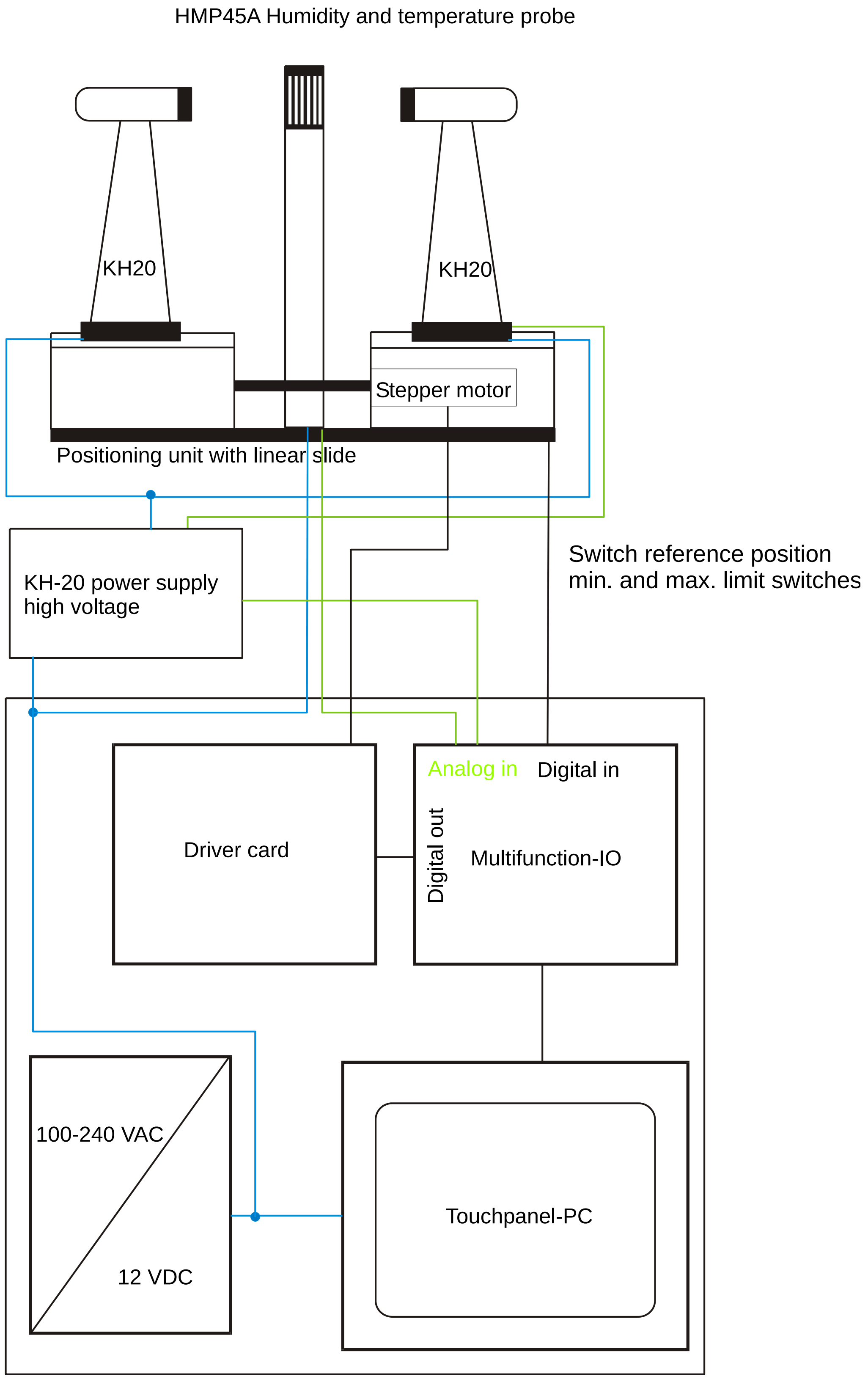
3 Construction of the Calibration Instrument

The design of the calibration instrument is made in contrast to the former version as one unit continuing a stepper motor system, PC and humidity sensor. The former system with in-situ calibration was not optimal to handle and continuous calibrations are not necessary. The new system is shown in Fig. 3. A schematic diagram of the instrument is Fig. 4. The standard accessory of the device is a HMP45A temperature-humidity sensor, a power-signal cable connection between the instrument and the high-voltage box of the krypton hygrometer, distance elements (2, 4 and 10 mm) for the fixing of the minimal path length and a calliper. The technical data of the instrument are given in Table 2



a) b)

Fig. 3: Calibration system a) with krypton hygrometer, stepping motor, HMP45A temperature-humidity sensor and tough panel PC, the switch, fuses and connector for hygrometer at the left site and USB as well as network connector ***(the PC is without virus scanner!)*** at the right site, and b) view in the box with tough panel PC in the background and power unit left, electronic for stepping motor middle and multifunction I/O module right (photographs: a) B. Mast, b) Th. Foken)



Block diagramm

Fig 4: Block schema of the Krypton hygrometer calibration instrument

Table 2: Technical data of the calibration instrument

instrument	data	value
calibration instrument	power	100-240 V, 50/60 Hz, 60 W
	fuse	2 x 1.6 A
	PC type	tough panel PC, 8.4”
	PC system	Windows XP embedded with Microsoft Framework 1.1
	maximal path range	min. path length + 28 mm
	minimal path length	2, 4 or 10 mm
	calibration range	1 – 20 g m^{-3} water vapour
		100 – 250 g m^{-3} oxygen
temperature-humidity sensor	type	HMP45A
	temperature	0 – 1 V, -40 – +60 °C
	humidity	0 – 1 V. 0 – 100 %
Krypton hygrometer KH20	power	12 V= from calibration instrument

The system has two limit switches. The optical one is the default. If it does not work because of its connection with the PC, an additional mechanical limit switch is included. To open the mechanical switch a reset switch is located on the right-hand side next to the screen (Fig. 5).

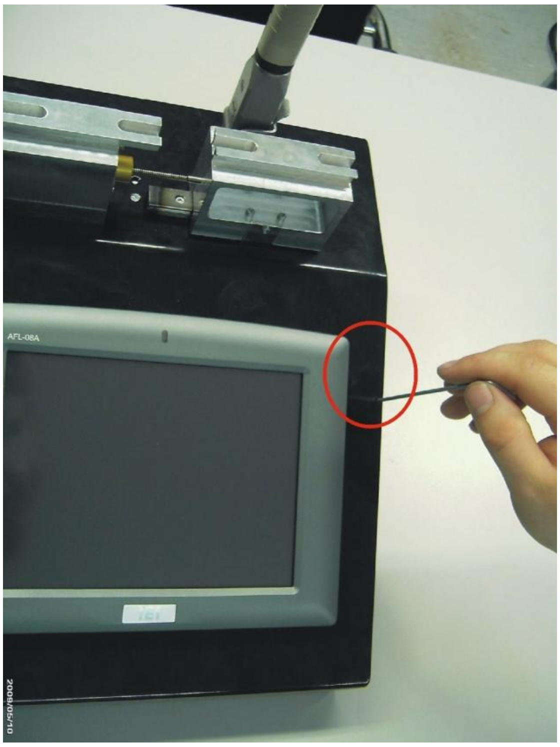


Fig. 5: Reset switch of the limit switches

4 Application of the Calibration Instruments

4.1 Preparation of the PC and basic setting

Switch on the system and the PC starts. Please create an additional user account (without administrator privileges) in case there is only the administrator account installed. Start from desktop “Kryptonhygro”. On the screen of “Kryptonhygro” you can also open “Explorer” and “On Screen Keyboard”.

If you start with a new project open ***>new<*** otherwise you can use an already existing project: ***>open<***. With ***>new<*** basic setup data are set to default values. Then ***>save<*** the file under the name with the next number (project*.cfg file given in the list) ***>save as<***. Each project is able to handle 10 Krypton hygrometers (devices). With this organization it is possible that one calibration instrument can be used by different users or for different sites organized indifferent projects. Each user or site can handle up to ten hygrometers.

4.2 Setup up of the basic data (project)

With the >setup< procedures all organizations of the PC can be done. First the ***>directory for measuring data<*** must be selected. It may be useful to have a different directory for each project.

The next step is to ***>adjust path range<*** with the different sub-steps: Give the minimal path length ***>min path<***, with 2 mm for high moisture; 4 mm for normal conditions, and 10 mm for very low moisture. After the calibration you can work with an optimal path length, which is different for each calibration. Often, it is useful to work with a ***>fixed path length<***, which should be in the optimal range but is constant during the use of the hygrometer. This recommended fixed path length is between 10 and 15 mm or according to the calibration protocol by Campbell Sci.

Do not change the default values of the following settings if not necessary. The ***>number notation<*** is the English notation. The ***>regression settings<*** are given in Chapter 3 or the help file. Do not change this default values if you are not familiar with the programme. The regression settings are made for indoor calibrations. For outdoor calibration the range for acceptance must be increased due to turbulent fluctuations. Only the morning or evening hours are applicable for outdoor calibrations.

Finally the ***>characteristics of the krypton hygrometers<*** must be included. Give all devices a consecutive number (0-9). Then include the ***>serial number<***, the **>K_w<** value, which is given in the calibration protocol of the producer (or which was determined for different moisture values by the applicant, this should be done in the laboratory because in nature the absolute humidity does not change within short time periods), and the **>K_O<** value which was determined shortly after the producer calibration or the last moisture calibration. Next give >***path 1***<, the actual path length of the sensor in **cm**, which is used before or given in the Campbell Sci. certificate. ***>Distance 2<*** gives the distance at the fixing in **cm**, which correspondences to the path length given before.

4.3 Installation of the sensor (device)

Remove the sensor from the fixing and fix the sensor to the calibration device. The sensor should not be fixed over the open part. **Do not forget to measure the length (Distance 2) between the fixings before you remove the sensor.**

Now use the ***>command<*** settings. First ***>select device<*** from the given list (see Chapter 4.2). Next is ***>adjust min path<*** and the sensor ***>move to minimal path<*** (see Chapter 4.2). If it is in the final position use the distance element (2, 4 or 10 mm according to the selected minimum path length) and bring the sensor to the minimum path by changing the fixing. If the device is in the right position you have to confirm you selection with ***>OK<***. Now the sensor ***>move backward 10 mm<*** and the distance element can be removed. If the device is in the right position you have to press ***>OK<***.

4.4 Calibration

Before you ***>execute<*** the different versions of the programme attach the sensor and the temperature-humidity sensor with the cable to the calibration unit. Execution without sensor does not work.

In the function ***>display<*** the registration of a time series is possible. In a new window you can set the path length and open the display. Here you can also move the sensor to all path lengths. The function ***>write to file<*** is analogue to ***>display<***, but all relevant data are stored. These functions are not connected with a calibration.

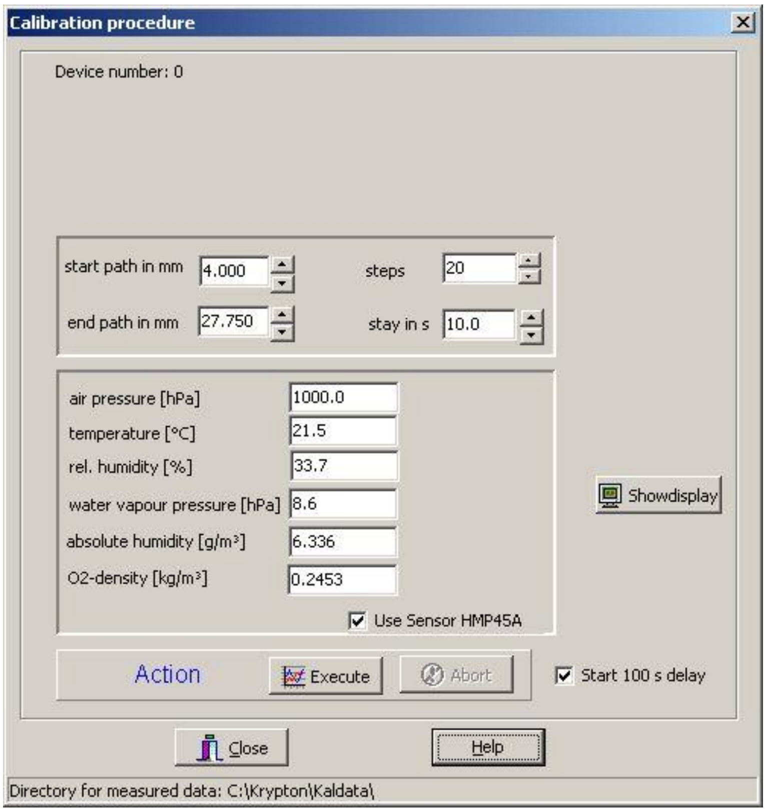
After starting the ***>calibration<*** several inputs are necessary, which will be stored after an successful calibration. These settings are the Number of data points ***>steps<***, typical 20, the duration for each data points ***>stay<***, typical 5-10 s, ***>start path in mm<*** for the start of the calibration, typical larger or equal minimal path length, ***>end path in mm<***, maximal path length is minimal path length + 28 mm, typical for normal conditions 20 mm (Fig. 6).

If the temperature-humidity sensor is not connected the humidity can be calculated with a moisture calculator from different input data. In all cases the local pressure must be given (see Chapter 4.4).

To determine the exact oxygen density an accurate pressure measurement in the level of the calibration is necessary. For instruments with a serial number 4 or higher a pressure sensor will be integrated into the instrument. The calculation of the oxygen density follows the equation

$$\rho_O = \frac{210(p-e)}{287.0586\,(t+273.15)\left(1+0.608\,\frac{0.622\,e}{p-0.378\,e}\right)} \tag{9}$$

with the air pressure p in hPa, the water vapour pressure e in hPa and the temperature in °C.



Device number: 0

start path in mm 4.000

end path in mm 27.750

steps 20

stay in s 10.0

air pressure [hPa] 1000.0

temperature [°C] 21.5

rel. humidity [%] 33.7

water vapour pressure [hPa] 8.6

absolute humidity [g/m³] 6.336

O2-density [kg/m³] 0.2453

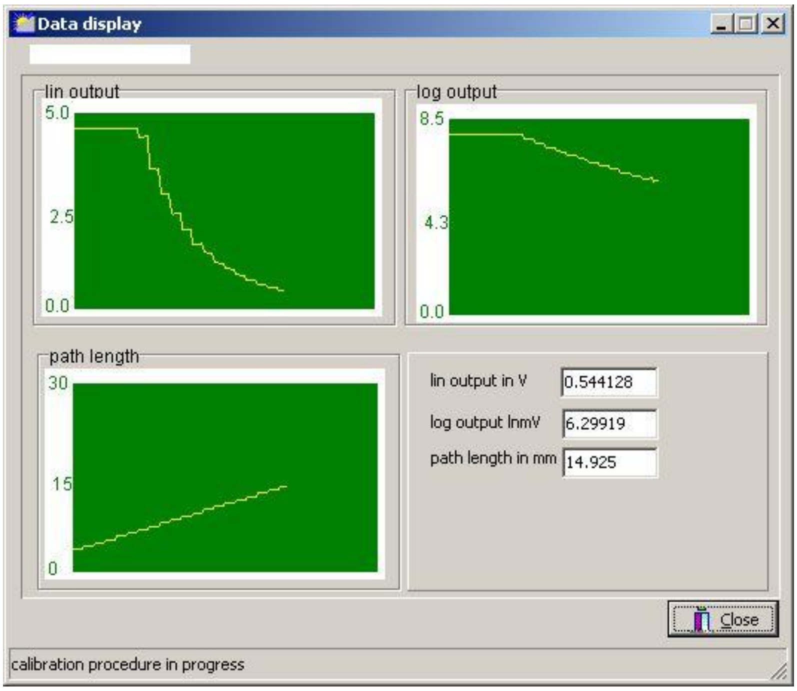
☑ Use Sensor HMP45A

☑ Start 100 s delay

Directory for measured data: C:\Krypton\Kaldata\

Fig. 6: Screen for the calibration settings

Now the system is ready to start the calibration. It is possible to use a delay time of 100 s that the operator is able to leave the calibration room. On a screen you can follow the calibration (Fig. 7). After completion of the calibration you see the calibration data for the previous calibration (if there was one) and the calibration for the fixed and an optimal path length. You have to select, which path length will be used for the comparison after the next calibration. For calibration files see Chapter 5.



lin output in V 0.544128

log output lnmV 6.29919

path length in mm 14.925

calibration procedure in progress

Fig. 7: Screen of the calibration control

4.4 Humidity calculator

The calibration unit has a temperature-humidity sensor HMP45A which measures the temperature t in °C and the relative humidity R. For the measured temperature the water vapour pressure for saturation can be determined (Sonntag 1990)

$$E(t) = 6.112\,\exp\left(\frac{17.62\,t}{243.12+t}\right) \tag{5}$$

for temperatures above 0°C and

$$E(t) = 6.112\,\exp\left(\frac{22.46\,t}{272.64+t}\right) \tag{6}$$

for temperatures below 0°C. The conditions can be selected on the screen. Now the water vapour pressure can be determined

$$e = R \cdot E(t)/100\% \tag{7}$$

and according to the gas low the absolute humidity a in g m^{-3}

$$a = \frac{216.67e}{t+273.15}. \tag{8}$$

Furthermore the input of the atmospheric pressure is necessary to determine the air density for further calculations.

In the case that no temperature-humidity sensor is available a humidity calculator can be opened. Necessary is the input of the temperature and the air pressure. For calculation of the absolute humidity it is possible to use one of the following humidity measures: relative humidity, dew point, moist temperature, water vapour pressure. The exact equations are given in Foken (2008).

4.5 Print of the calibration protocol

The Windows version of the tough panel PC is not compatible with a printer driver or pdf maker (do not try this!). Therefore the programme writes two calibration file (see Chapter 5) and a protocol as *.wmf, which you can recognized by all Word versions.

You can also copy the project file and the calibration output file on another PC. On a second PC unzip the file “kryptonprintcertificate.zip” and copy the calibration und project files into this folder. Now you can generate the calibration protocol (see Appendix A).

5 Data Input and Output Formats

The programs and files of the calibration are given in Table 3.

Table 3: File type of the calibration and necessary programs

file type	file name	remarks
project file	projecty.cfg	y: number of project (0-9)
calibration data	MMDDSSMM.khx	Month, day, hour, minute; x= logical number of device (0-9)
results of calibration (for comparison with next calibration)	MMDDSSMM.kcx	
calibration protocol	MMDDSSMM.wmf	
calibration program, no installation necessary, updates can be downloaded*)	Krypton.zip with:	Zip-program with all files:
	kryptonhygro.exe	program
	khmath.dll	
	kryptoncontrol.exe	multifunction I/O
	Nationalinstruments.Common.dll	
	Winterdom.IO.FileMap.dll	
	krypton.chm	helpfile
	logobt.bmp	logo Micrometeorology
	logogaf.bmp	logo GAF
print program, no installation necessary	Kryptonprintcertificate.exe	on a second PC

*) http://www.bayceer.uni-bayreuth.de/mm/en/software/software/software_dl.php?id_obj=78287

6 References

Ackerman M (1971) UV-solar radiation related to mesospheric processes. In: Fiocco G (ed.), Mesospheric Models and Related Experiments. D. Reidel Publishing Company, Dordrecht, 149-159.

Buck AL (1973) Development of an improved Lyman-alpha hygrometer. Atm Technol. 2:213-240.

Buck AL (1976) The variable-path Lyman-alpha hygrometer and its operating characteristics. Bull Amer Meteorol Soc. 57:1113-1118.

Campbell GS and Tanner BD (1985) A Krypton hygrometer for measurement of atmospheric water vapour concentrations, Moisture and humidity. ISA, Research Triangle Park, 609-614.

Finlayson-Pitts BJ and Pitts JN (2000) Chemistry of the upper and lower atmosphere. Academic Press, San Diego, 963 pp.

Foken T, Dlugi R and Kramm G (1995) On the determination of dry deposition and emission of gaseous compounds at the biosphere-atmosphere interface. Meteorol Z. 4:91-118.

Foken T, Buck AL, Nye RA and Horn RD (1998) A Lyman-alpha hygrometer with variable path length. J Atm Oceanic Techn. 15:211-214.

Foken T (2008) Micrometeorology. Springer, Berlin, Heidelberg, 308 pp.

Johns JWC (1965) The absorption of radiation by water vapor. In: Ruskin RE (ed.), Humidity and moisture, measurement and control in science and industry, vol. 1, Principles and methods of measuring humidity in gases. Reinhold, New York, 417-427.

Kretschmer SI and Karpovitsch JV (1973) Maloinercionnyj ultrafioletovyj vlagometer (Sensitive ultraviolet hygrometer). Izv AN SSSR, Fiz Atm Okeana. 9:642-645.

Martini L, Stark B and Hunsalz G (1973) Elektronisches Lyman-Alpha-Feuchtigkeitsmessgerät. Z Meteorol. 23:313-322.

Mota R, et al. (2005) Water VUV electronic state spectroscopy by synchrotron radiation. Chem Phys Lett. 416:152-159.

Ogawa S and Ogawa M (1975) Absorption cross sections of O2(a1Δg) and O2(X3Σg−) in the region from 1087 to 1700 Å Can J Phys. 53:1845-1852.

Sonntag D (1990) Important new values of the physical constants of 1986, vapour pressure formulations based on the ITC-90, and psychrometer formulae. Z Meteorol. 40:340-344.

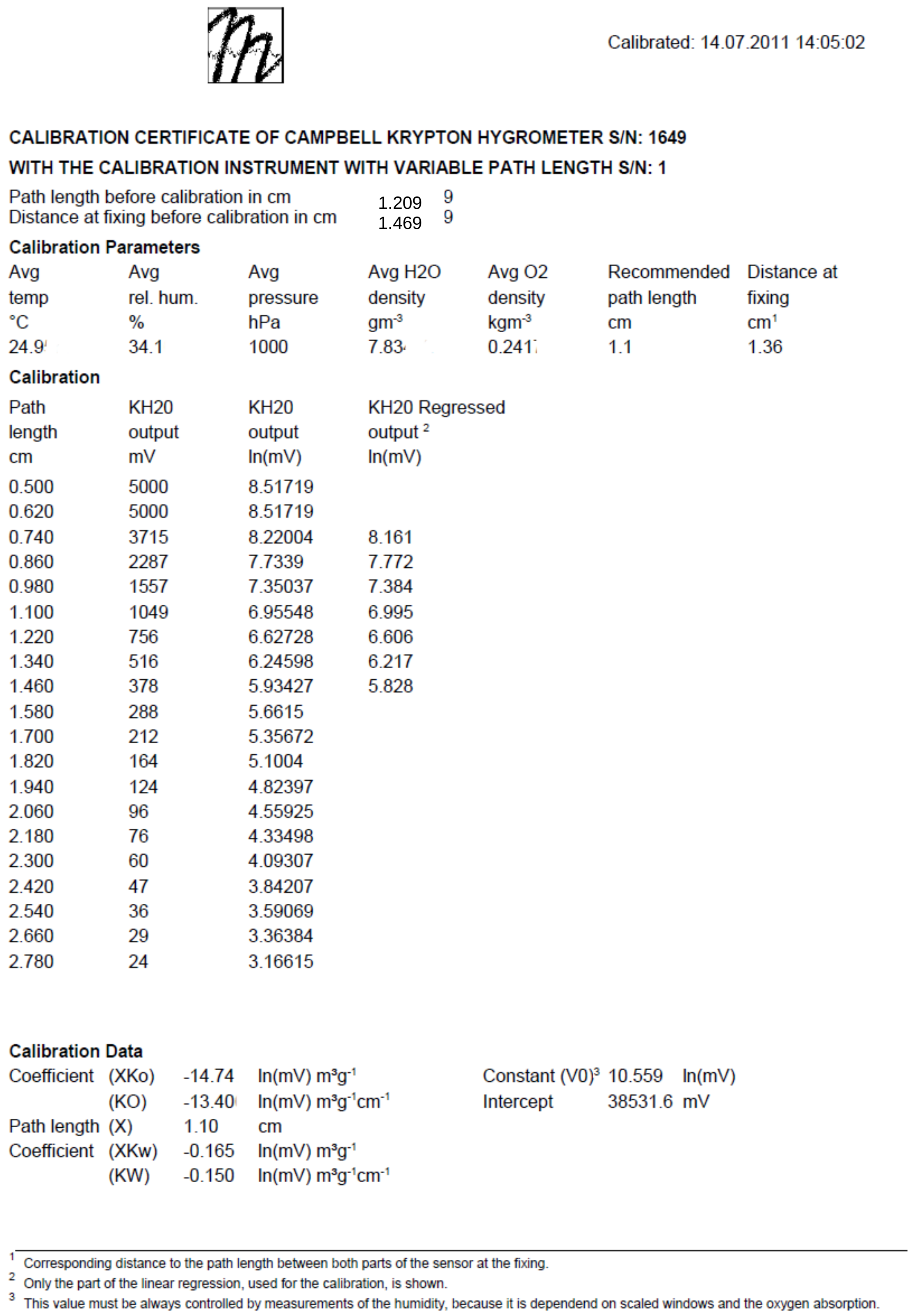
Tanner BD, Swiatek E and Greene JP (1993) Density fluctuations and use of the krypton hygrometer in surface flux measurements. In: Allen RG (ed.), Management of irrigation and drainage systems: integrated perspectives. American Society of Civil Engineers, New York, NY, 945-952.

Tillman JE (1965) Water vapor density measurements utilizing the absorption of vacuum ultraviolet and infrared radiation. In: Ruskin RE (ed.), Humidity and moisture, Measurement and control in Science and industry, vol. 1, Principles and methods of measuring humidity in gases. Reinhold, New York, 428-433.

van Dijk A, Kohsiek W and DeBruin HAR (2003) Oxygen sensitivity of krypton and Lyman-alpha hygrometers. J Atm Oceanic Techn. 20:143-151.

Watanabe K and Zelikoff M (1953) Absorption coefficient of water vapor in the vacuum ultraviolett. J Opt Soc Am. 43:753-754.

Appendix A: Sample Calibration protocol



Calibrated: 14.07.2011 14:05:02

CALIBRATION CERTIFICATE OF CAMPBELL KRYPTON HYGROMETER S/N: 1649

WITH THE CALIBRATION INSTRUMENT WITH VARIABLE PATH LENGTH S/N: 1

Path length before calibration in cm	1.209	9
Distance at fixing before calibration in cm	1.469	9

Calibration Parameters

Avg temp °C	Avg rel. hum. %	Avg pressure hPa	Avg H2O density gm^{-3}	Avg O2 density kgm^{-3}	Recommended path length cm	Distance at fixing cm[1]
24.9	34.1	1000	7.83	0.241	1.1	1.36

Calibration

Path length cm	KH20 output mV	KH20 output ln(mV)	KH20 Regressed output [2] ln(mV)
0.500	5000	8.51719	
0.620	5000	8.51719	
0.740	3715	8.22004	8.161
0.860	2287	7.7339	7.772
0.980	1557	7.35037	7.384
1.100	1049	6.95548	6.995
1.220	756	6.62728	6.606
1.340	516	6.24598	6.217
1.460	378	5.93427	5.828
1.580	288	5.6615	
1.700	212	5.35672	
1.820	164	5.1004	
1.940	124	4.82397	
2.060	96	4.55925	
2.180	76	4.33498	
2.300	60	4.09307	
2.420	47	3.84207	
2.540	36	3.59069	
2.660	29	3.36384	
2.780	24	3.16615	

Calibration Data

Coefficient	(XKo)	-14.74	ln(mV) m^3g^{-1}	Constant (V0)[3]	10.559	ln(mV)
	(KO)	-13.40	ln(mV) $m^3g^{-1}cm^{-1}$	Intercept	38531.6	mV
Path length	(X)	1.10	cm			
Coefficient	(XKw)	-0.165	ln(mV) m^3g^{-1}			
	(KW)	-0.150	ln(mV) $m^3g^{-1}cm^{-1}$			

---

[1] Corresponding distance to the path length between both parts of the sensor at the fixing.

[2] Only the part of the linear regression, used for the calibration, is shown.

[3] This value must be always controlled by measurements of the humidity, because it is dependend on scaled windows and the oxygen absorption.

Appendix 2: Sample Calibration file *.kcx

```
File: 07141405.kc0

S/N: 1649
water vapour pressure [hPa];abs. hum. [g/m³];airpressure [hPa];dry tempera-
ture [°C];wet temperature [°C];dew point [°C];rel. humidity [%];O2density
[kg/m³];
10.7808;7.83412;1000;25.0177;-9999;-9999;;34.10340.241717
first in regression;last in regression;
3;9;
path [cm];lin voltage [mV];log voltage [ln mV];
0.5;5000;8.51719
0.62;5000;8.51719
0.74;3714.68;8.22004
0.86;2287.23;7.7339
0.98;1556.81;7.35037
1.1;1048.92;6.95548
1.22;755.667;6.62728
1.34;515.957;6.24598
1.46;377.775;5.93427
1.58;287.59;5.6615
1.7;212.032;5.35672
1.82;164.092;5.1004
1.94;124.462;4.82397
2.06;95.5192;4.55925
2.18;76.3407;4.33498
2.3;59.9335;4.09307
2.42;46.639;3.84207
2.54;36.2726;3.59069
2.66;28.9104;3.36384
2.78;23.7212;3.16615
```

Appendix 3: Accessories kit

Included accessories kit:

- distance elements: 2, 4 and 10 mm
- connection cable for Krypton hygrometer
- power cable
- temperature-humidity sensor HMP45A with special connector
- 2 fuse 1.6 A
- pen for tough panel PC
- CD with the software image, which can be copied on the CF card of the PC

Additional items necessary for operation:

- calliper (accuracy 0.1 mm)
- Phillips-tip screwdriver
- memory stick

Volumes in the series ‚University of Bayreuth, Department of Micrometeorology, Arbeitsergebnisse'

Nr	Author(s)	Title	Year
01	Foken	Der Bayreuther Turbulenzknecht	01/1999
02	Foken	Methode zur Bestimmung der trockenen Deposition von Bor	02/1999
03	Liu	Error analysis of the modified Bowen ratio method	02/1999
04	Foken et al.	Nachfrostgefährdung des ÖBG	03/1999
05	Hierteis	Dokumentation des Experimentes Dlouhá Louka	03/1999
06	Mangold	Dokumentation des Experimentes am Standort Weidenbrunnen, Juli/August 1998	07/1999
07	Heinz et al.	Strukturanalyse der atmosphärischen Turbulenz mittels Wavelet-Verfahren zur Bestimmung von Austauschprozessen über dem antarktischen Schelfeis	07/1999
08	Foken	Comparison of the sonic anemometer Young Model 81000 during VOITEX-99	10/1999
09	Foken et al.	Lufthygienisch-bioklimatische Kennzeichnung des oberen Egertales, Zwischenbericht 1999	11/1999
10	Sodemann	Stationsdatenbank zum BStMLU-Projekt Lufthygienisch-bioklimatische Kennzeichnung des oberen Egertales	03/2000
11	Neuner	Dokumentation zur Erstellung der meteorologischen Eingabedaten für das Modell BEKLIMA	10/2000
12	Foken et al.	Dokumentation des Experimentes VOITEX-99	10/2000
13	Bruckmeier et al.	Documentation of the experiment EBEX-2000, July 20 to August 24, 2000	01/2001
14	Foken et al.	Lufthygienisch-bioklimatische Kennzeichnung des oberen Egertales	02/2001
15	Göckede	Die Verwendung des Footprint-Modells nach Schmid (1997) zur stabilitätsabhängigen Bestimmung der Rauhigkeitslänge	03/2001
16	Neuner	Berechnung der Evaporation im ÖBG (Universität Bayreuth) mit dem SVAT-Modell BEKLIMA	05/2001
17	Sodemann	Dokumentation der Software zur Bearbeitung der FINTUREX-Daten	08/2002
18	Göckede et al.	Dokumentation des Experiments STINHO-1	08/2002
19	Göckede et al.	Dokumentation des Experiments STINHO-2	12/2002
20	Göckede et al	Characterisation of a complex measuring site for flux measurements	12/2002
21	Liebethal	Strahlungsmessgerätevergleich während des Experiments STINHO-1	01/2003
22	Mauder et al.	Dokumentation des Experiments EVA_GRIPS	03/2003
23	Mauder et al.	Dokumentation des Experimentes LITFASS-2003, Dokumentation des Experimentes GRASATEM-2003	12/2003
24	Thomas et al.	Documentation of the WALDATEM-2003 Experiment	05/2004
25	Göckede et al.	Qualitätsbegutachtung komplexer mikrometeorologischer Messstationen im Rahmen des VERTIKO-Projekts	11/2004
26	Mauder & Foken	Documentation and instruction manual of the eddy covariance software package TK2	12/2004
27	Herold et al.	The OP-2 open path infrared gas analyser for $CO_2$and H_2O	01/2005
28	Ruppert	ATEM software for atmospheric turbulent exchange measurements using eddy covariance and relaxed eddy accumulation systems and Bayreuth whole-air REA system setup	04/2005

29	Foken (Ed.)	Klimatologische und mikrometeorologische Forschungen im Rahmen des Bayreuther Institutes für Terrestrische Ökosystemforschung (BITÖK), 1989-2004	06/2005
30	Siebeke & Serafimovich	Ultraschallanemometer-Überprüfung im Windkanal der TU Dresden 2007	04/2007
31	Lüers & Bareiss	The Arctic Turbulence Experiment 2006 PART 1: Technical documentation of the ARCTEX 2006 campaign, May, 2nd to May, 20th 2006	07/2007
32	Lüers & Bareiss	The Arctic Turbulence Experiment 2006 PART 2: Visualization of near surface measurements during the ARCTEX 2006 campaign, May, 2nd to May, 20th 2006	07/2007
33	Bareiss & Lüers	The Arctic Turbulence Experiment 2006 PART 3: Aerological measurements during the ARCTEX 2006 campaign, May, 2nd to May, 20th 2006	07/2007
34	Metzger & Foken et al.	COPS experiment, Convective and orographically induced precipitation study, 01 June 2007 – 31 August 2007, Documentation	09/2007
35	Staudt & Foken	Documentation of reference data for the experimental areas of the Bayreuth Centre for Ecology and Environmental Research (BayCEER) at the Waldstein site	11/2007
36	Serafimovich et al.	ExchanGE processes in mountainous Regions (EGER) - Documentation of the Intensive Observation Period (IOP1), September, 6th to October, 7th 2007	01/2008
37	Serafimovich et al.	ExchanGE processes in mountainous Regions (EGER) - Documentation of the Intensive Observation Period (IOP2), June, 1st to July, 15th 2008	10/2008
38	Siebicke	Footprint synthesis for the FLUXNET site Waldstein/Weidenbrunnen (DE-Bay) during the EGER experiment.	12/2008
39	Lüers & Foken	Jahresbericht 2008 zum Förderprojekt 01879 - Untersuchung der Veränderung der Konzentration von Luftbeimengungen und Treibhausgasen im hohen Fichtelgebirge 2007 – 2013	01/2009
40	Lüers & Foken (Eds.)	Proceedings of the International Conference of "Atmospheric Transport and Chemistry in Forest Ecosystems" Castle of Thurnau, Germany, Oct 5 to Oct 8, 2009	10/2009
41	Biermann et al.	Mesoscale circulations and energy and gas exchange over the Tibetan Plateau – Documentation of the micrometeorological experiment, Nam Tso, Tibet , 25 June 2009 – 08 August 2009	12/2009
42	Foken & Falke	Documentation and Instruction Manual for the Krypton Hygrometer Calibration Instrument	01/2010