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Abt. Mikrometeorologie

Documentation and Instruction Manual for the Krypton Hygrometer Calibration Instrument

In cooperation with

Gesellschaft für Akustik und Fahrzeugmesswesen mbH, Zwickau

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Content

1 Introduction

Fast response hygrometers are nowadays an important part of all measuring complexes for turbulent energy fluxes. There was 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 was increased and the production results much easier.

The Lyman-alpha hygrometer was developed at the beginning of the 70s nearly parallel in USA, 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 hygrometers 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 was not directly located in the Lyman-alpha band and has a cross sensitivity to oxygen (see Chapter 2). Infrared hygrometers are commercially available since the 90s but first instrument developments are dated 30 years earlier (for overview see Foken *et al.* 1995).

All these hygrometer types are working on the basis of Lambert-Beer's low:

$$I = I_0 \exp\left(-\rho_w k x\right) \qquad (1)$$

with the current at the receiver I_0 and of the lamp I, the absolute humidity ρ_w, the absorption coefficient k and the path length between lamp and receiver x. While emission and detection efficiency I_0 affects I, I_0 is not affecting 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 is usually made for different absolute humidities at fixed path lengths. Because the hydrogen and the krypton lamps are not very stable in time the calibrations in a moisture chamber are not very useful during field campaigns. 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. (Foken *et al.* 1998). A simple application of this system is impossible, because the Krypton hygrometer works with two absorption lines and both with two absorbers. Nevertheless such a development is necessary because IR hygrometers are not sensitive enough to measure absolute humidities below 2-4 g m^{-3}. But such low humidity's 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 a prototype 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 major band at 123.58 nm and a minor band at 116.49 nm. 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 Figure 1.

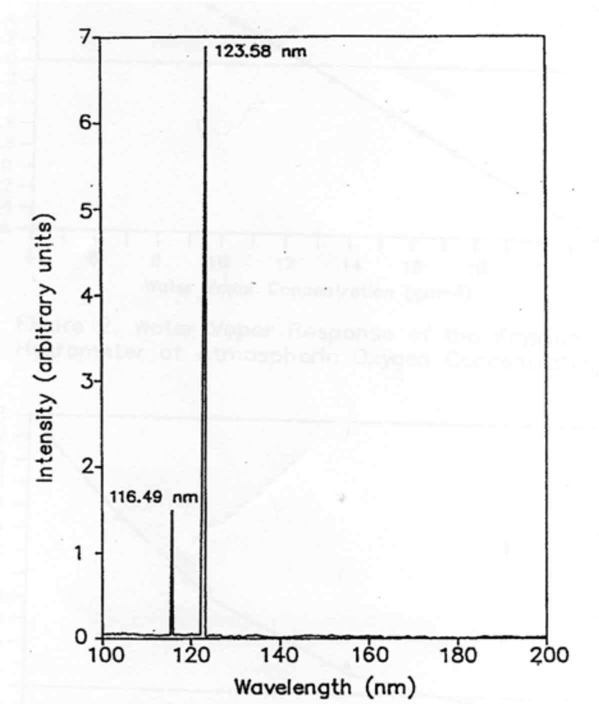

Figure 1: Spectrum of the krypton lamp (Campbell and Tanner 1985, courtesy Scientific Services, Rocky Hill, NJ)

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

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

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

According to Tillman (1965) the absorption coefficient in the short wavelength is by factor 2 smaller than in the long wavelength. Because of this fact and that only the signal of both 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

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

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 (like on aircrafts) 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 or a change in path length, it is possible to alter the path length for nearly constant humidity conditions in order to simulate a change in humidity. : For in-situ calibration this makes the determination of actual calibration characteristics and the optimal path length possible.

The simplification of Eq. (2) given in Eq. (3) cannot be used to determine an effective absorption coefficient. The different absorption coefficients in both bands must be taken into account while the path length is changing. The absorption coefficient for water vapour in band 1 is approximately k_{w1} ~ 70 cm^{-1} and for band 2 approximately k_{w2} ~ 130 cm^{-1} (Johns 1965; Watanabe and Zelikoff 1953), see Figure 2. Because of the different absorption coefficients in both spectral lines it was necessary to include an effective path length in such a way that the absorption coefficient of path 1 becomes the weight 1 and the path length is equal to the real path length *X*. Accordingly the effective path length is the sum of the weighted path length of both spectral lines,

$$X_{eff} = \frac{X\ (k_{w1} + k_{k2})}{k_{w1}} + c_2 = X\ c_1 + c_2 \tag{5}$$

with c_1 ~ 2.8. The coefficient c_2 is approximately 1.0-1.2 cm and is dependent on the scaled window and the oxygen absorption. It has no influence on the sensitivity of the instrument.

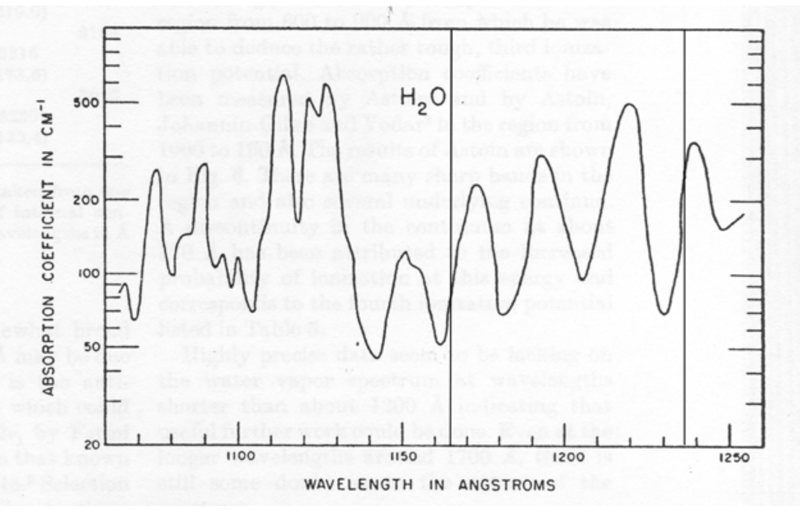

Figure 2: Absorption coefficient of water vapour in the relevant spectral lines (Johns 1965)

The effective path length is only used in the internal regression programme according to

$$\ln(V) = \ln(V0)_{eff} - a \cdot X_{eff} \cdot Kw_{eff} \tag{6}$$

The effective path length is only an internal parameter for the calibration procedure. For direct application one should use the path length and the calibration equation by Campbell Sci. according to Eq. (4).

2.3 Calibration procedure

The calibration procedure follows the calibration protocol of the of the Krypton hygrometer KH20 by Campbell Sci. But instead of different absolute humidities the path length is changed. For about 15-20 different path lengths the output signal must be measured in order to receive a sufficient number of calibration points. It is assumed that the most exact points of the calibration are in the center of the used range of calibration. The regression according the Eq. (6) starts with a minimum of 5 measuring points [ln V, X_{eff}] for a given absolute humidity. Measuring points will be added into the regression as long as the linearity is given according to the test parameters of the calibration given in Table 1. If the regression is not well correlated or is not linear, the calibration must be repeated. 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 Figure 3.

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

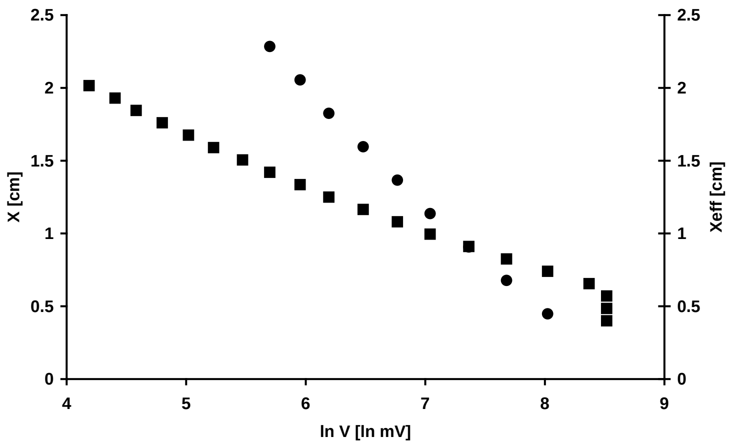

Figure 3: Example of a calibration diagram with the measuring points (squares) in relation to the path length *X* and for the linear range the effective path length X_{eff} (circles), device KH20 No. 1649, Bayreuth 08.05.2009, $\rho_w = 7.9$ g m^{-3}

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

constant V_0 in [ln (mV)]

coefficient K_w in [ln(mV) m^3 g^{-1} cm^{-1}]

for a given measuring path length X [cm] also the coefficient XK_w in [ln(mV) m^3 g^{-1}] is given.

The optimal path length is in the center of the linear calibration range. This parameter should help to inform the researcher whether the chosen path length was optimal according to the operational environment (absolute humidity).

The Campbell Sci. calibration protocol includes calibrations for clean and scaled windows and different ranges of the humidity. All Campbell devices are calibrated for an altitude of > 1000 m a.s.l. with a lower oxygen concentration than the one 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 neglected, but the calibration can 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 contining 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 Figure 4. A schematic diagram of the instrument is Figure 5. 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)

Figure 4: 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: Th. Foken)

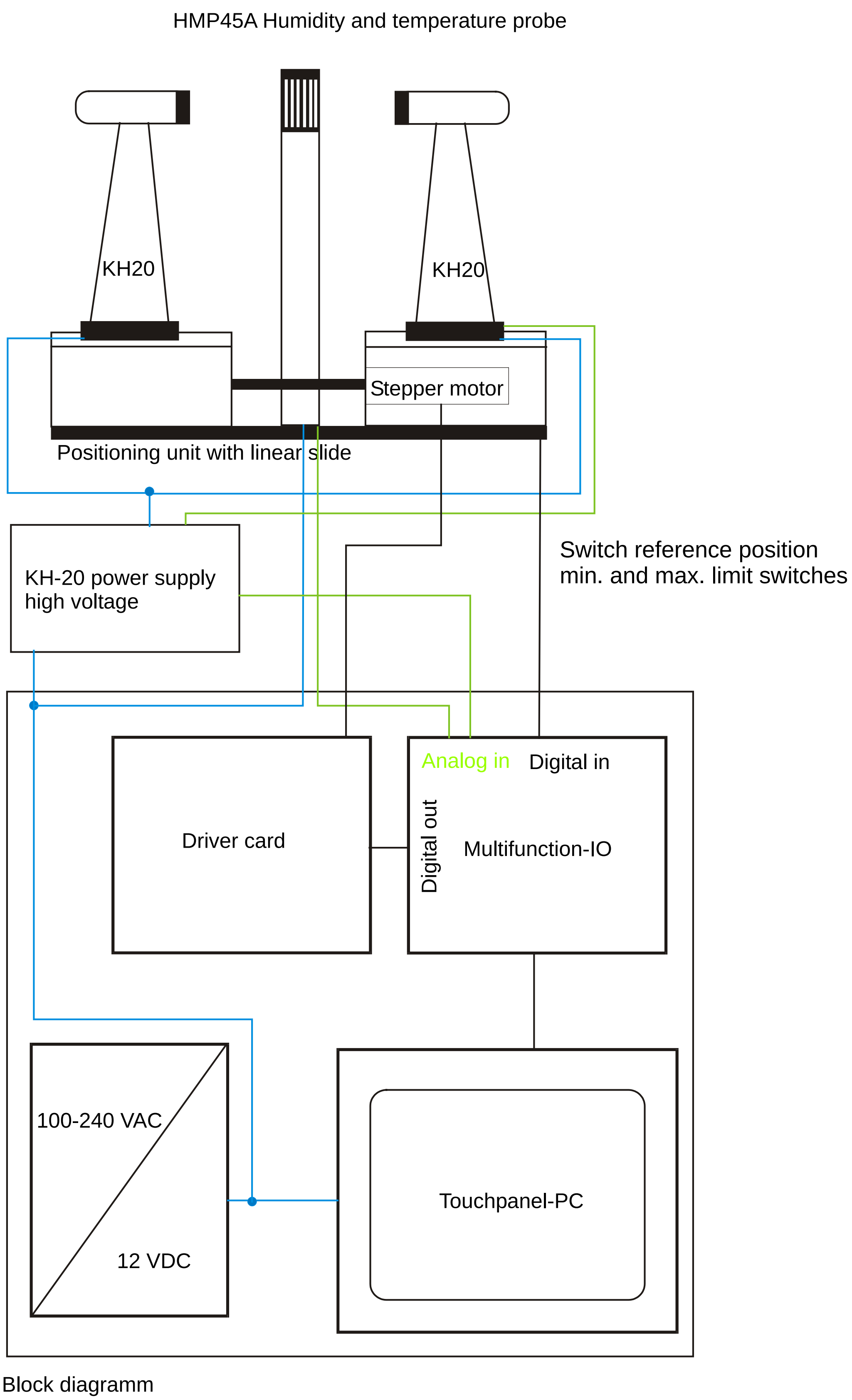

Figure 5: Block schema of the Krypton hygrometer calibration instrument

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
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 (Figure 6).

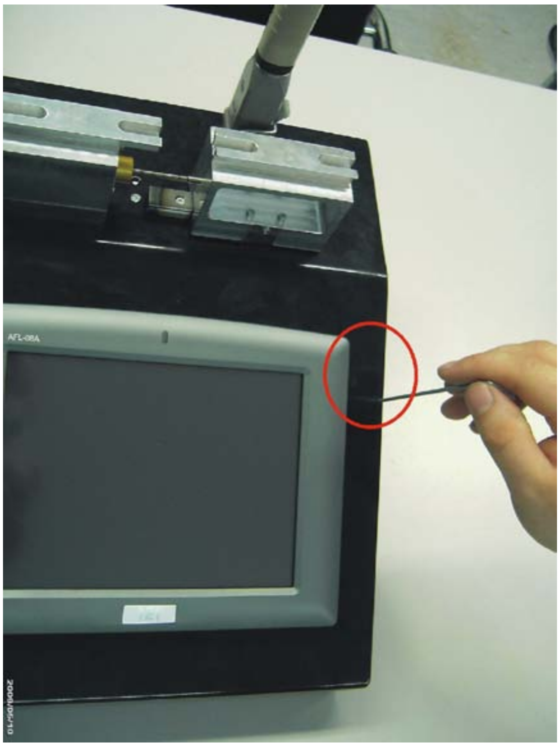

Figure 6: Reset switch of the limit switches

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 a n 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 ***>b<*** value (b=2.7), which depends on the sensitivity of both beams of the Krypton hygrometer and the ***>c<*** value (c=1.55) for each device. This value can be changed, if the windows are dirty or for low pressure conditions, this value is responsible for the calibration of the absolute value, the fluctuations are always well calibrated. 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 (Figure 7).

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 4.5).

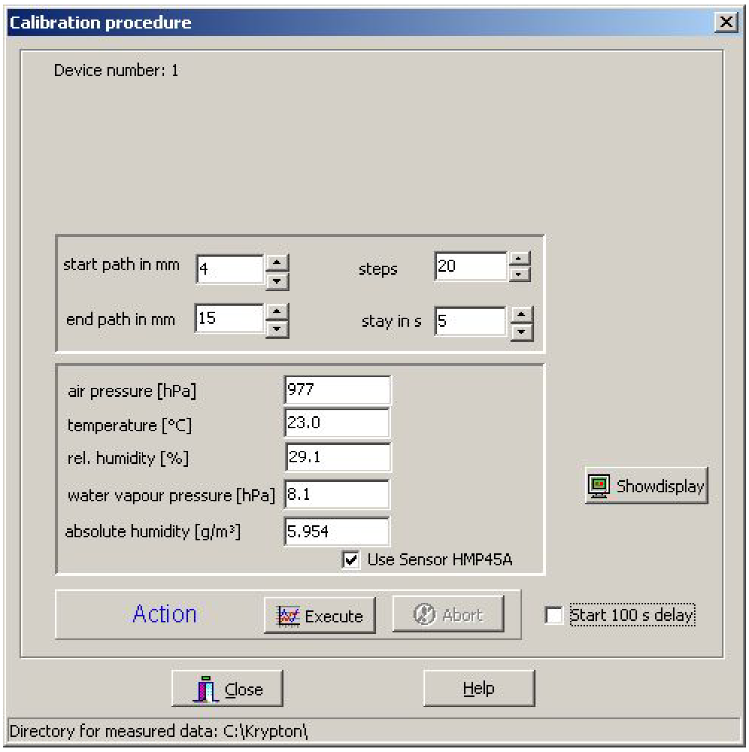

Figure 7: Screen for the calibration settings

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 (Figure 8). 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.

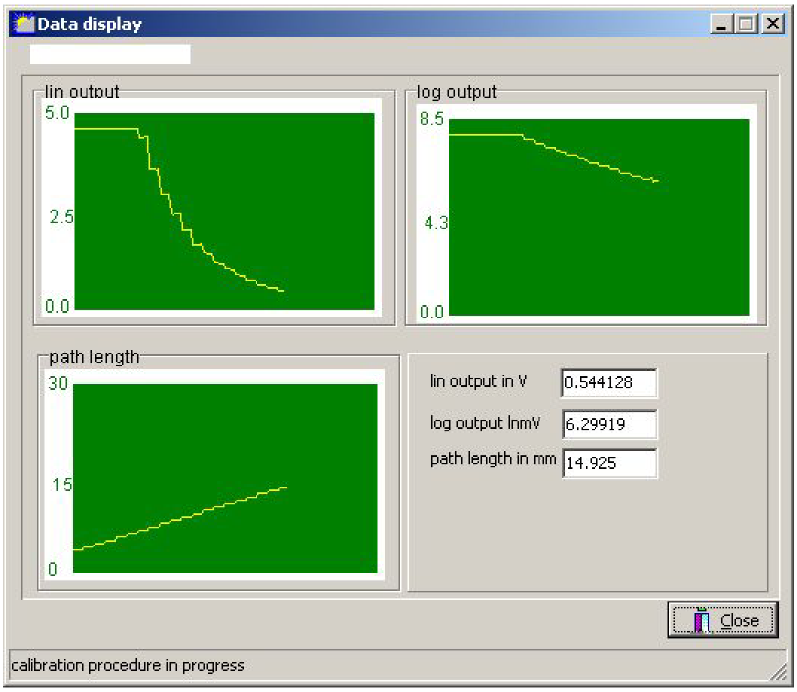

Figure 8: Screen of the calibration control

4.5 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)

$$E(t) = 6.112 \exp\left(\frac{17.62\, t}{243.12 + t}\right) \tag{7}$$

for temperatures above 0°C and

$$E(t) = 6.112 \exp\left(\frac{22.46\, t}{272.64 + t}\right) \tag{8}$$

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

$$e = R \cdot E(t) / 100\% \tag{9}$$

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

$$a = \frac{216.67 e}{t + 273.15}. \tag{10}$$

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).

4.6 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: kryptonhygro.exe khmath.dll kryptoncontrol.exe Nationalinstruments.Common.dll Winterdom.IO.FileMap.dll krypton.chm logobt.bmp logogaf.bmp	Zip-program with all files: program multifunction I/O helpfile logo Micrometeorology 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

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Watanabe, K, 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: 1/29/2010 5:16:53 PM

CALIBRATION CERTIFICATE OF CAMPBELL KRYPTON HYGROMETER S/N: 1649

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

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

Calibration Parameters

Avg temp °C	Avg rel. hum. %	Avg pressure hPa	Avg H2O density gm^{-3}	Avg O2 density gm^{-3}	Recommended path length cm	Distance at fixing cm[1]
21.5692	26.123	990	4.946	0.244074	1.25	1.51

Calibration

Path length cm	Eff. Path length cm	KH20 output mV	KH20 output ln(mV)	KH20 Regressed output[2] ln(mV)
0.400	-0.470	5000	8.51719	
0.485	-0.240	5000	8.51719	
0.570	-0.011	5000	8.51719	
0.655	0.219	5000	8.51719	
0.740	0.448	4918	8.50069	
0.825	0.677	3709	8.21841	8.152
0.910	0.907	2816	7.9432	7.927
0.995	1.137	2178	7.68615	7.702
1.080	1.366	1715	7.44704	7.476
1.165	1.596	1344	7.20364	7.251
1.250	1.825	1080	6.98484	7.026
1.335	2.054	874	6.77251	6.800
1.420	2.284	710	6.56454	6.575
1.505	2.514	591	6.38144	6.350
1.590	2.743	484	6.18166	6.124
1.675	2.973	404	6.00149	5.899
1.760	3.202	340	5.82877	
1.845	3.432	284	5.65047	
1.930	3.661	242	5.4893	
2.015	3.891	209	5.34183	

Used effective path length[3]

effective path length = 2.700 * path length - 1.550 cm

Calibration Data

Coefficient	(XKw)	-0.24812	ln(mV) m^3g^{-1}	Constant (V0)[4]	8.81750	ln(mV)
	(Kw)	-0.19850	ln(mV) $m^3g^{-1}cm^{-1}$	Intercept	6751.1	mV
Path length	(X)	1.250	cm			

[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] The effective path length is used for the calibration and takes into account the two beams and the oxygen absorption.

[4] 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: 01291716.kc3

S/N: 1649
water vapour pressure [hPa] abs. hum. [g/m³] airpressure [hPa] dry temperature
[°C] rel. humidity [%]
6.72662 4.946 990 21.5234 26.2756
first in regression last in regression
6 16
path [cm] lin voltage [mV] log voltage [ln mV]
0.4 5000 8.51719
0.485 5000 8.51719
0.57 5000 8.51719
0.655 5000 8.51719
0.74 4918.19 8.50069
0.825 3708.64 8.21841
0.91 2816.45 7.9432
0.995 2177.98 7.68615
1.08 1714.79 7.44704
1.165 1344.35 7.20364
1.25 1080.15 6.98484
1.335 873.567 6.77251
1.42 709.503 6.56454
1.505 590.846 6.38144
1.59 483.873 6.18166
1.675 404.075 6.00149
1.76 339.956 5.82877
1.845 284.434 5.65047
1.93 242.114 5.4893
2.015 208.978 5.34183
```

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

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