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Technical Note: Calibration instrument for the krypton hygrometer KH20

T. Foken^{1,3} and H. Falke²

¹University of Bayreuth, Department of Micrometeorology, Germany

²Gesellschaft für Akustik und Fahrzeugmesswesen mbH, Zwickau, Germany

³Member of Bayreuth Center of Ecology and Environmental Research (BayCEER), University of Bayreuth, Germany

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Correspondence to: T. Foken (thomas.foken@uni-bayreuth.de)

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Abstract

A calibration instrument for krypton hygrometers (KH20, Campbell Sci.) with variable path length is presented. This unit allows for in-situ calibrations of the krypton hygrometer, which is typically not very stable over time, during measuring campaigns. It was constructed mainly for application at high altitudes and low temperatures, where further improvements are needed to the IR-hygrometers which are normally used. The changing path length requires that a changing concentration of the absorber be simulated. Because oxygen absorbs more strongly than water vapour, the calibration is made against oxygen and transferred to water vapour. The design of the calibration instrument is made as one unit containing a stepper motor system, PC and humidity sensor. For the calibration, it is necessary to install the krypton hygrometer on this unit.

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 yr. While sensors which were commercially available in the 90s of the previous century mainly used UV absorption lines (Foken et al., 1995), at present there is almost exclusive use of sensors working with the IR absorption lines. This is because 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. At the same time, the sensitivity of IR-sensors has been increased and while these sensors have only been commercially available since the 90s, the first instrument developments are dated 30 yr 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

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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 Sect. 2).

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

$$I = I_0 \exp(-\rho_w k x) \quad (1)$$

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 practical during field campaigns, the calibration with variable path length was developed. According to Eq. (1) the calibration with a changing path length is also possible 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, a development is necessary because IR hygrometers are not very sensitive in measuring absolute humidities below $2\text{--}4 \text{ g m}^{-3}$, 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 and is presented in this paper.

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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.

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

$$I = I_0 \exp(-x k_w) [f \exp(-x k_{o1} \rho_{o1}) + (1-f) \exp(-x k_{o2} \rho_{o2})] \quad (2)$$

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

$$I = I_0 \exp(-x k_w \rho_w) [f \exp(-x k_{o1} \rho_{o1}) + (1-f) \exp(-x k_{o2} \rho_{o2})] \quad (3)$$

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

$$\ln(I) = \ln(I_0) - \alpha \cdot X \cdot K_w \quad (4)$$

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with the constant V_0 in \ln (mV), approximately $8 \dots 10 \ln(\text{mV})$, the intercept $\exp(\ln V_0)$ in mV, the calibration coefficient (effective absorption coefficient for water vapour) K_w in $\ln(\text{mV}) \text{ m}^3 \text{ g}^{-1} \text{ cm}^{-1}$, the coefficient XK_w in $\ln(\text{mV}) \text{ m}^3 \text{ g}^{-1}$ for a given path length X in cm and the absolute humidity a in g m^{-3} .

- 5 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

- 10 Since a change in the output signal can be produced by either a change in humidity and oxygen or 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 2×10^3 (Tillman, 1965), while the ratio of the densities is typically about 2×10^{-1} and therefore the effect of the water vapour is 100-fold 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 on the same order when the partial density of oxygen is at least twentyfold higher. 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 1 $k_{w1} = 28.5 (\text{atm at } 298 \text{ K})^{-1} \text{ cm}^{-1}$ and for band 2 $k_{w2} = 49.5 (\text{atm at } 298 \text{ K})^{-1} \text{ cm}^{-1}$, see Fig. 2. Ogawa and Ogawa (1975)¹ reported

¹Data from "MPI-Mainz-UV-VIS Spectral Atlas of Gaseous Molecules" (<http://www.atmosphere.mpg.de/enid/2295>)

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- 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 $k_{o1} = 19.9 (\text{atm at } 298 \text{ K})^{-1} \text{ cm}^{-1}$ (nearly identical with the water vapour absorption) and for band 2: $k_{o2} = 32.5 (\text{atm at } 298 \text{ K})^{-1} \text{ cm}^{-1}$, less than one tenth of the water vapour absorption. Furthermore, in this spectral range the absorption maximum of ozone with about $k_{o31} \approx 83 (\text{atm at } 298 \text{ K})^{-1} \text{ cm}^{-1}$ and $k_{o32} \approx 170 (\text{atm at } 298 \text{ K})^{-1} \text{ cm}^{-1}$ 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.

- Because the signal of band 1 is more than 20% lower than those of band 2 due to the lower intensity (Fig. 1) and the smaller width of the band, an estimate of the error resulting from the use of oxygen as a proxy for the calibration can be easily made using the ratio of the water vapour and oxygen absorption in the band 2, which is $k_{w2}/k_{o2} = 1.5$. With a typical ratio of the densities for oxygen of 240 g m^{-3} and water vapour of 10 g m^{-3} , it follows that the cross sensitivity of water is less than 10%, and for low water vapour pressure, which is the typical application range of Krypton hygrometers, even lower than 5%.

- For the calibration with variable path length, the simplification of Eq. (2) given in Eq. (3) cannot be used to determine an effective absorption coefficient. But the assumption will be made that Eq. (2) can be written analogous to Eq. (3) with only one output signal as a combination of both spectral lines in the form

$$I = I_0 \exp \left\{ -x \left[\frac{f}{1-f} (k_{w1} \rho_{w1} + k_{o1} \rho_{o1}) + k_{w2} \rho_{w2} + k_{o2} \rho_{o2} \right] \right\} \quad (5)$$

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

$$I = I_0 \exp(-x k_o \rho_o) \quad (6)$$

- 25 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:

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- 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

$$\ln(V) = \ln(V_0) - \rho_o \cdot x \cdot K_o \quad (7)$$

By comparison of the coefficient K_o of the oxygen calibration with the value of K_o from 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. 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.

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.

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3 Calibration instrument and calibration procedure

3.1 Calibration instrument

The calibration instrument is designed as one unit containing a stepper motor system, PC and humidity sensor. The system is shown in Fig. 3. A schematic diagram of the instrument is given in Fig. 4. The standard accessory of the device is a HMP45A temperature-humidity sensor, which measures the temperature and the relative humidity. It is also possible to use other humidity instruments, and the calibration instrument therefore includes a humidity calculator. Together with an external pressure sensor, these data are necessary to calculate the air density and therefore the oxygen partial density used in Eq. (7). Relevant textbooks can be consulted for the calculations. The krypton hygrometer is connected with the standard connection cables to the calibration unit. For calibration the KH20 must be fixed on the calibration unit. To determine the exact path length the minimal path length of calibration can be set with distance elements (2, 4 and 10 mm). It is possible to start the calibration after a delay time of 100 s which allows the operator to leave the calibration location. The calibration (Fig. 5) can be followed on a screen. After completion of the calibration, the calibration data together with the previous calibration will be shown and written into a file. Furthermore, a calibration protocol will be created similar to the original one. More detail about the instrument and the handling are given by Foken and Falke (2010).

3.2 Calibration procedure

The calibration procedure follows the calibration protocol of the krypton hygrometer KH20 by Campbell Sci., with the exception that 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 range of calibration used. The regression according to Eq. (7) starts with a minimum of 5

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measuring points $[\ln V, X]$ for a given air density. 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. Because of the non-ideal log-linear response characteristics of the krypton hygrometer, the range and the accuracy of the log-linear approximation (which is the calibration used in most of the turbulence calculation programmes) is responsible for the accuracy of the calibration. There are two calibration modes: indoor and outdoor calibration. The indoor calibration using typical outdoor conditions (temperature, humidity) 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 the calibration on the control screen is given in Fig. 5, and of the calibration curve in Fig. 6. Here the regression in the linear part of the calibration, which is identical with the linear part of the response characteristics of the krypton hygrometer, is shown between the logarithm of the output signal and the path length according to Eq. (7). The partial densities of ozone and water vapour should be constant during the calibration. The error of the calibration method is mainly related to the accuracy of the linear approximation. Therefore, it is recommended that at least three calibrations be made within a short time period. The calibrations typically differ by less than 5% (Table 1). This includes the error of the linearization and influences of pressure and humidity fluctuations during the calibration. Reasons for mis-calibrations can be excessively large pressure or humidity fluctuations (outdoor), or a non-steady state environment (indoor), which allows no log-linear approximation. Other sources of errors, like the temperature and humidity effect on the air density, are negligible because they are much lower than 1%. For the example given in Fig. 6, the cross sensitivity due to water vapour is 4.9% according to the calculation given in Sect. 2.2. Normally the absolute humidity ρ_w has no daily cycle like the relative humidity, and significant changes occur only with a change of the air masses. Applying different calibrations for different classes of absolute humidity can reduce the cross sensitivity. The cross sensitivity is even smaller for the typical application of krypton hygrometers under low water

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vapour concentrations. The error – which is therefore mainly related to the degree to which it is possible to linearize the log-linear calibration – is given above as typically less than 5%.

With the water vapour and oxygen calibration for a new instrument the determined oxygen calibration will be re-calculated into a water vapour calibration with the relation

$$K_{w\text{-new}} = K_{w\text{-old}} \frac{K_{o\text{-new}}}{K_{o\text{-old}}} \quad (8)$$

The first oxygen calibration should be done within the few weeks for which Campbell Sci. guaranties the constancy of the calibration coefficient. 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 (Table 1), 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_w in [ln(mV) $\text{m}^3 \text{g}^{-1} \text{cm}^{-1}$], and the coefficient XK_w in [ln(mV) $\text{m}^3 \text{g}^{-1}$] 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.

3.3 Improvement of the calibration

A prototype of the instrument was successfully tested during several experiments, and the described version during both laboratory measurements at Bayreuth (Germany) and two expeditions on the Tibetan Plateau. The calibration in Bayreuth for a new krypton hygrometer was equal to that of Campbell scientific, and on the Tibetan Plateau the data obtained after calibration followed a reference device well. The calibration coefficients found are given in Table 2. A further test under winter conditions (water vapour density about $1\text{--}2 \text{g m}^{-3}$) showed a lower sensitivity and the necessity to increase the

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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 prior calibration in %/100 %	0.05	0.1

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Table 2. Results of calibrations of the Krypton Hygrometer no. 1649 (produced 2009); remark: K_w and K_o are the calibration coefficients, the sensitivity is the reciprocal value.

Date/Place	Oxygen density in g m^{-3}	K_w in $\text{ln(mV) m}^3 \text{g}^{-1} \text{cm}^{-1}$ for constant oxygen concentration	K_o in $\text{ln(mV) m}^3 \text{g}^{-1} \text{cm}^{-1}$ for constant water vapour concentration
Campbell Sci., Logan UT, 1340 m a.s.l.		-0.1573	
Bayreuth, Germany, 340 m a.s.l., 8 May 2009	250.43		-13.607
NamCo, China, 4730 m a.s.l., 25 June 2009	144.90	-0.1573/0.79	-17.223
NamCo, China, 4730 m a.s.l., 5 July 2010	145.51	-0.1573/0.67	-20.231

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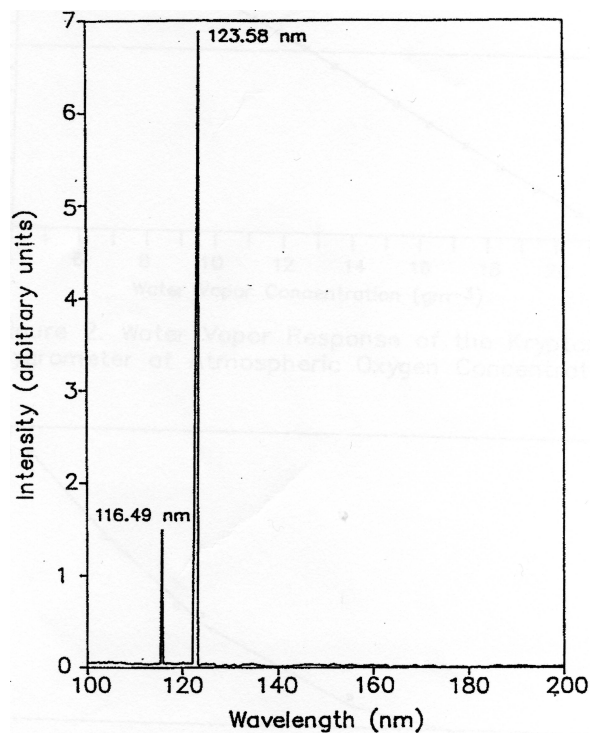


Fig. 1. Spectrum of the krypton lamp (Campbell and Tanner, 1985, courtesy Scientific Services, Rocky Hill, NJ).

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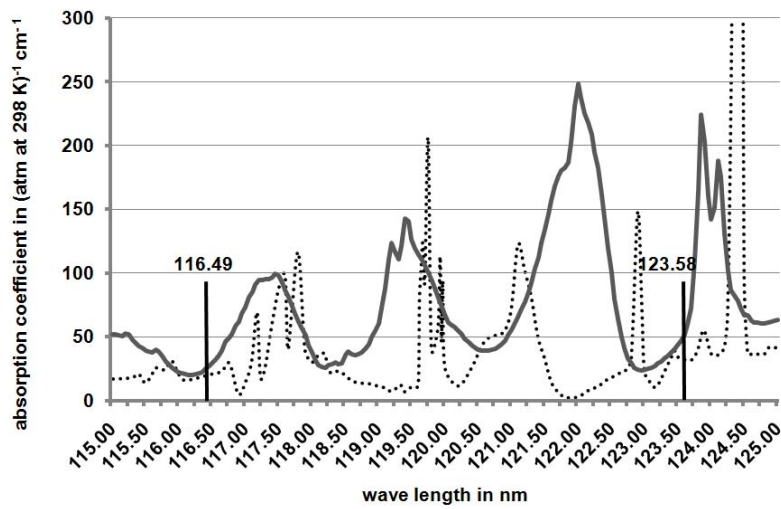


Fig. 2. Absorption coefficient of water vapour in the relevant spectral lines with the data given by Mota et al. (2005) and for oxygen (dotted line) with data given by Ogava and Ogava (1975) and transformed from base e to base 10 (Finlayson-Pitts and Pitts, 2000).

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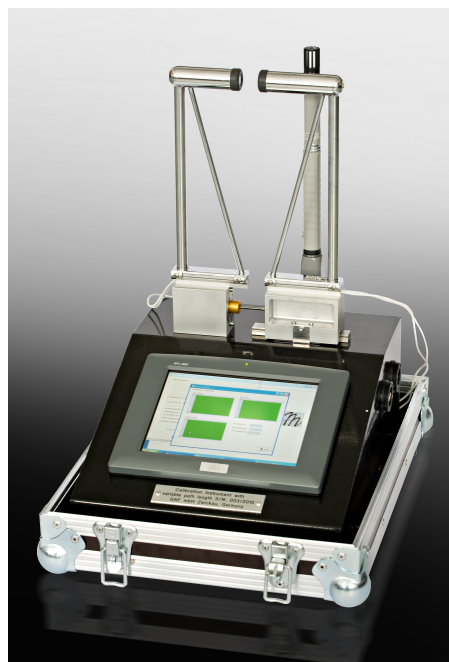


Fig. 3. Calibration system with krypton hygrometer, stepping motor, HMP45A temperature-humidity sensor and tough panel PC, the switch, fuses and connector for hygrometer at the left side and USB as well as network connector at the right side (photograph: B. Mast).

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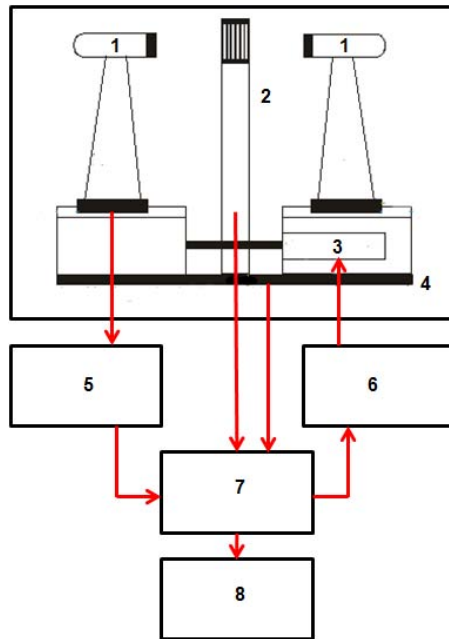


Fig. 4. Block schema of the krypton hygrometer calibration instrument: 1: KH20, 2: HMP45A, 3: stepper motor, 4: positioning unit with linear slide, 5: amplifier (part of KH20), 6: driver, 7: multifunction-IO, 8: touchpanel PC, the power supply units are not shown.

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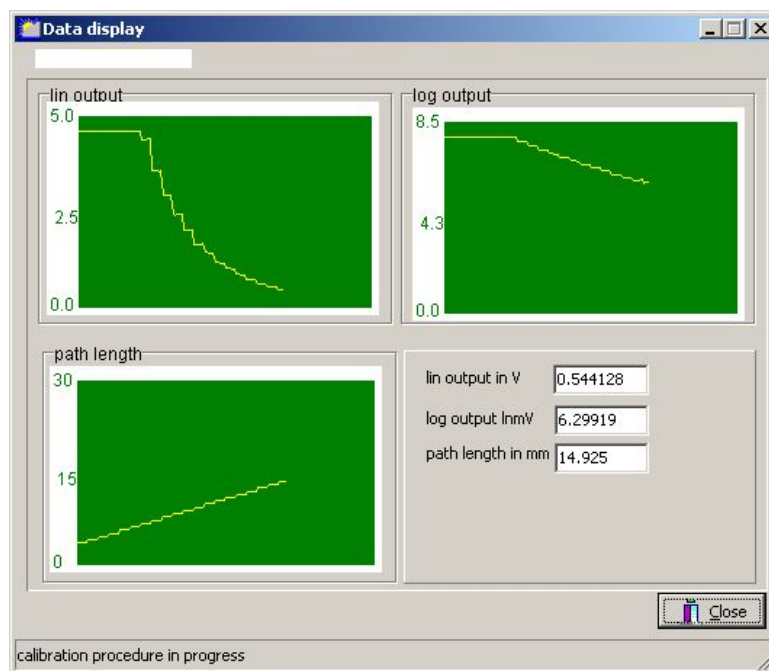


Fig. 5. Screen of the calibration control with the linear (above left) and logarithmic (above right, comparable with Fig. 6) output signals and the steps of the changing path length (below left).

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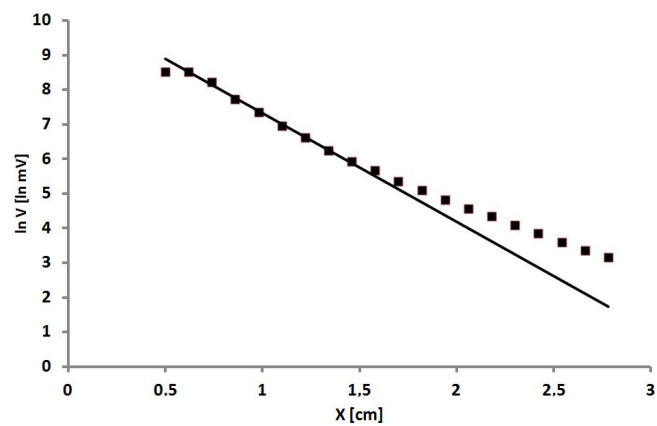


Fig. 6. Example of a calibration diagram, with the measuring points (squares) of the logarithmical output signal in relation to the path length X for nearly constant partial density of water vapour and oxygen (note that this appears similar to the original calibration curve from Campbell Sci., except that there the abscissa represents the absolute humidity for constant path length), and the regression line in the nearly log-linear part of the response function, device KH20 No. 1649, Zwickau 14 July 2011, $\rho_w = 7.8 \text{ g m}^{-3}$, $\rho_o = 241 \text{ g m}^{-3}$.