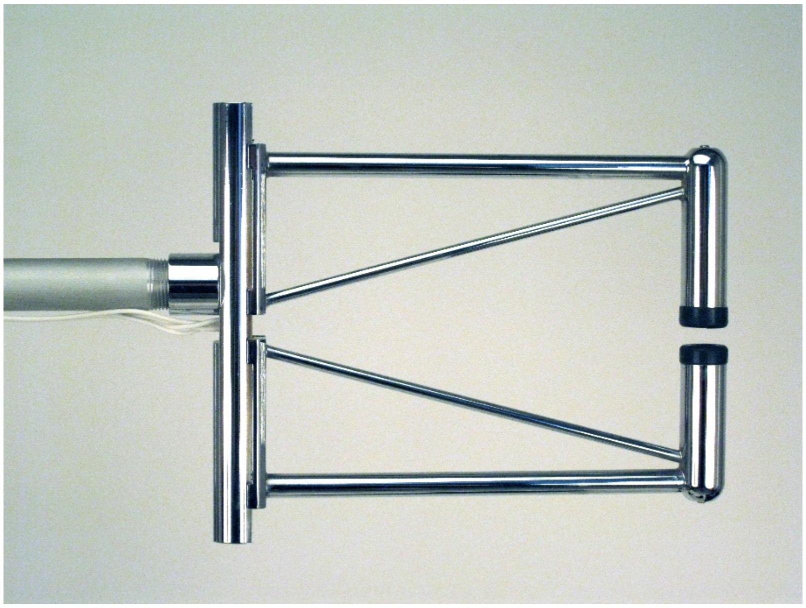
Product Manual

Sensor

KH20

Krypton Hygrometer



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KH20 Krypton Hygrometer

1. Introduction

The KH20 is a highly sensitive hygrometer designed for measurement of rapid fluctuations in atmospheric water vapor, not absolute concentrations. It is typically used together with a CSAT3B in eddy-covariance systems.

2. Precautions

- READ AND UNDERSTAND the *Safety* section at the back of this manual.
- Although the KH20 is rugged, it should be handled as precision scientific instrument.

3. Initial Inspection

- Upon receipt of the KH20, inspect the packaging and contents for damage. File damage claims with the shipping company.
- The model number and cable length are printed on a label at the connection end of the cable. Check this information against the shipping documents to ensure the correct product and cable length are received (see Section 3.1, *Components* (p. 1)).

3.1 Components

The KH20 sensor consist of a sensor head with 2 m (6 ft) cables and an electronics box. The following are also shipped with the KH20:

- KH20CBL-L25 Power/Signal cable with 8 m (25 ft) length. If a longer cable is desired, order a KH20CBL-L replacement cable and specify the desired length after -L (for example KH20CBL-L50).
- 1/2 Unit Desiccant Bag
- Rain Shield
- Horizontal Mounting Boom (51 cm 20 mm DN (20-inch 3/4 IPS) threaded aluminum pipe)
- 3/4 x 3/4 in. Nu-Rail Crossover Fitting
- 4 mm (5/32 in) Allen Wrench

4. Overview

The KH20 is a krypton hygrometer for measuring water vapor fluctuations in the air. The name KH20 (KH-twenty) was derived from KH2O (K-H_2O), and the sensor has been known with this name since 1985. It is typically used with the CSAT3B 3-D sonic anemometer for measuring latent heat flux (LE), using eddy-covariance technique.

The KH20 sensor uses a krypton lamp that emits two absorption lines: major line at 123.58 nm and minor line at 116.49 nm. Both lines are absorbed by water vapor, and a small amount of the minor line is absorbed by oxygen. The KH20 is not suitable for absolute water vapor concentration measurements due to its signal offset drift.

The KH20 heads are sealed and will not suffer damage should they get wet. In addition, the electronics box and the connectors are housed inside a rain shield that protects them from moisture. The KH20 is suitable for long-term continuous outdoor applications.

The KH20 sensor is comprised of two main parts: the sensor head and the electronics box. The sensor head comes with cables that connect the sensor to the electronics, a power/signal cable, and mounting hardware.

NOTE Discussion on the principles and theory of measurement is included in Appendix A, *Coefficient Calculations* *(p. A-1)*.

Features:

- High frequency response suitable for eddy-covariance applications
- Well-suited for long-term, unattended applications
- Compatible with Campbell Scientific CRBasic data loggers: CR6, CR3000, CR1000X, CR800 Series, CR1000, CR5000, and CR9000(X)

5. Specifications

5.1 Measurements

Range:	1.7 to 19.5 g/m^3 (nominal)
Frequency Response:	100 Hz
Operating Temperature Range:	–30 to 50 °C

5.2 Electrical

Supply Voltage:	10 V to 16 VDC
Current Consumption:	20 mA max at 12 VDC
Power Consumption:	0.24 Watts
Output Signal Range:	0 to 5 VDC

5.3 Physical

Dimensions	
Sensor Head:	29 x 23 x 3 cm (11.5 x 9 x 1.25 in)
Electronics Box:	19 x 13 x 5 cm (7.5 x 5 x 2 in)
Rain Shield with Mount:	29 x 18 x 6.5 cm (11.5 x 7 x 2.5 in)
Mounting Pipe:	50 cm (20 in)
Carrying Case:	64 x 38 x 18 cm (25 x 15 x 7 in)

Weight

Sensor Head:	1.61 kg (3.55 lb)
Electronics Box:	0.6 kg (1.4 lb)
Rain Shield with Mount:	2.2 kg (4.75 lb)
Mounting Pipe with Nu-rail:	0.45 kg (1.0 lb)
Carrying Case:	4.3 kg (9.45 lb)
Shipping:	9.2 kg (20.15 lb)

6. Installation

6.1 Siting

When installing the KH20 sensor for latent heat flux measurement in an eddy-covariance application, proper siting, sensor height, sensor orientation and fetch are important.

6.2 Mounting

6.2.1 Parts and Tools Needed for Mounting

The following user-supplied hardware is required to mount the KH20 sensor:

1. Tripod (CM115 standard) or tower
2. Campbell Scientific crossarm (CM204 standard)
3. 3/4-inch IPS Aluminum Pipe, 12 inches long
4. 3/4-inch-by-1-inch Nu-Rail Crossover Fitting
5. Small Phillips and flat-head screwdrivers
6. 1/2-inch wrench

6.2.2 Mounting the KH20 Sensor

Mount the KH20 sensor head as follows:

1. Attach the 51 cm (20 in) mounting boom to the KH20.
2. Mount a crossarm to a tripod or tower.
3. Mount the 12-inch-long pipe to a crossarm via 1-inch-by-3/4-inch Nu-Rail Crossover Fitting.
4. Mount the KH20 onto the 30 cm (12 in) pipe using a 3/4-inch-by-3/4-inch Nu-Rail Crossover Fitting. Mount the KH20 such that the source tube, the longer of the two tubes, is positioned on top, as shown in FIGURE 6-1. Use cable ties to secure loose cables to the tripod or tower mast.

FIGURE 6-1. Mounting KH20 to a tripod

6.2.3 Mounting the Electronics Box

Mount the electronics box as follows:

1. Remove the front cover of the rain shield by loosening the two pan-head screws on the bottom front of the rain shield, and then pushing the cover all the way up, and sliding it out.

NOTE It will be difficult to mount the rain shield to a mast with the front cover on, since the 1/2-inch nut holding the bottom U-bolt is located inside the rain shield.

2. Before mounting the rain shield to a tripod, first mount the electronics box inside the rain shield. Remove the four pan-head screws from the back panel of the rain shield. Align the electronics box and use the four pan-head screws to secure the electronics box onto the back panel. Make sure the electronics box is pushed all the way up, and the screws are positioned at the bottom of the mounting slot on the electronics box. This will provide enough room to attach the connectors to the bottom of the electronics box later.

NOTE If the electronics box is not pushed all the way up during mounting, you will not have enough room to attach the connectors to the bottom of the electronics box, as the U-bolt for the rain shield will block the position of the connectors.

3. Mount the rain shield onto the tripod or tower mast using the U-bolt provided. Make sure that the distance between the KH20 sensor head and the rain shield is within 5 feet so that the cables from the sensor head will be within reach of the electronics box. Also make sure that the rain shield is mounted vertically with an opening pointing downward so that the rain will effectively run down the rain shield and not penetrate inside.

4. Connect the three cables to the bottom of the electronics box around the U-bolt on the rain shield (see FIGURE 6-2). If there is not enough room for the connectors around the U-bolt, make sure the electronics box is mounted at a highest possible position (see step 2).

FIGURE 6-2. Attaching cables to the electronics box

5. Place the front cover back on the rain shield and tighten the two pan-head screws to secure it in place.

FIGURE 6-3. Electronics box with front cover

6. Gather any loose cables and tie them up, using cable ties, onto the tripod or tower mast.

FIGURE 6-4. KH20, CSAT3B, and electronic box mounted on a mast

6.3 Wiring

TABLE 6-1. Wire Color, Function, and Data Logger Connection

Wire	Wire Label	Data Logger Connection Terminal
White	Signal	**U** configured for differential input[1], **DIFF H** (differential high, analog-voltage input)
Black (from white/black set)	Signal Reference	**U** configured for differential input[1, 2], **DIFF L** (differential low, analog-voltage input)[2]
Red	Power 12V	**12V**
Black (from red/black set)	Power Ground	**G**
Clear	Shield	⏚ (analog ground)

[1]**U** terminals are automatically configured by the measurement instruction.
[2]Jumper to ⏚ with a user-supplied wire.

6.4 Data Logger Programming

The KH20 sensor outputs 0 to 5 VDC analog signal. These signals can be measured using the VoltDiff instruction on the CRBasic data loggers.

Programming basics for CRBasic data loggers are in the following sections. Complete program examples for select CRBasic data loggers can be found in Appendix B, *Example Program* *(p. B-1)*.

6.4.1 Coefficient Determination

Each KH20 reports data over a vapor range of approximately 2 to 19 g/m^3. Calculations are performed under the following conditions: window clean and scaled. The water vapor absorption coefficient for three different vapor ranges are calculated from the report data: full range, dry range, and wet range. TABLE 6-2 shows a sample of the KH20 vapor ranges over which three different water vapor absorption coefficients are calculated. See Appendix A, *Coefficient Calculations* *(p. A-1)*, for more information.

TABLE 6-2. KH20 Ranges

Ranges	Vapor Density (g/m^3)
Full Vapor Range	2 – 19
Dry Vapor Range	2 – 9.5
Wet Vapor Range	8.25 – 19

Before the water vapor absorption coefficient, k_w, is entered into the data logger program for the KH20, the following decisions must be made:

- Will the windows be allowed to scale?
- What vapor range is appropriate for the site?

Once the decision is made, the appropriate k_w can be chosen from the data report. The data report also contains the path length, x, for a specific KH20. Using the water vapor absorption coefficient for either the dry or the wet vapor range will produce more accurate measurements than using that for the full range. If the vapor range of the site is unknown, or if the vapor range is on the border line between the dry and the wet vapor ranges, the full range should be used.

7. Maintenance

The KH20 sensor is designed for continuous field application and requires little maintenance. The tube ends for the KH20 have been sealed with silicone elastomer using an injection-mold method. Therefore, the tubes are protected from water damage, and the KH20 continues to make measurements under rainy or wet conditions. If the water tends to pool up on the tube window and blocks the signal, turn the sensor head at an angle so as to shed the water off the tube window. The rain shield protects the electronics box and the connectors from moisture.

7.1 Visual Inspection

- Make sure the optical windows are clean.
- Inspect the cables and connectors for any damage or corrosion. If you see a discoloration on the white co-axial cable, you may suspect that the cable has water damage.

7.2 Testing the Source Tube

The source tube is the longer of the two tubes. Check to see if the source tube is working properly by performing the following test.

First, make sure the UV light is emitted from the source tube. To do this, you may look into the source tube (the longer of the two tubes), and you should see a bright blue light emitted from it.

NOTE Avoid looking into the source tube for an extended period of time when the KH20 is powered on to minimize the prolonged exposure to the UV light.

If you see a faint or flickering blue light, perform the following test.

Check the current drain on the KH20

> Typical current drain for the KH20 during normal operation should be 15 ~ 20 mA. The current drain of around 5 mA or less indicates the problem on the source tube. Obtain an RMA from Campbell Scientific and send the unit in for repair.

Check the voltage signal output from the KH20

> If the voltage output reading is below 50 mV, you may have problems with either the source tube or the detector tube (Section 7.3, *Testing the Detector Tube* (p. 8)).

7.3 Testing the Detector Tube

If the source tube tests fine but the output from KH20 is still in question, perform the following test. Prepare a piece of paper and insert it between the source tube and the detector tube to completely block the optical path. You should see an immediate decrease in the voltage reading, and it should go close to zero. No noticeable change in the voltage output, when the optical path is completely blocked, indicates a problem in the detector tube. If the decrease in the voltage reading takes place but the reading remains below 50 mV, when the paper is removed from the optical path, the source tube may be at fault. Obtain an RMA from Campbell Scientific and send the unit in for repair.

7.4 Managing the Scaling of KH20

The KH20 cannot be used to measure an absolute concentration of water vapor, because of scaling on the source tube windows caused by disassociation of atmospheric continuants by the ultra violet photons (Campbell and Tanner, 1985 and Buck, 1976). The rate of scaling is a function of the atmospheric humidity. In a high humidity environment, scaling can occur within a few hours. That scaling attenuates the signal and can cause shifts in the coefficient curve. However, the scaling over a typical flux averaging period is small. Thus, water vapor fluctuation measurements can still be made with the hygrometer.

To see if the source tube window has been scaled, get a clean, dry cotton swab and slide it across the source tube window. The scale is not visible to the naked eye, but if the window is scaled, you will feel a slight but noticeable resistance while you slide the swab across the window. There will be little resistance if the window is not scaled. If you determine the window is scaled, you can clean it with a wet cotton swab.

Use distilled water and a clean cotton swab to clean the scaled window. After cleaning the window, slide a clean, dry swab across the window to confirm the scale has been removed.

NOTE You can use the water vapor absorption coefficient for scaled window from the data report if the window will be allowed to scale during measurements.

7.5 Coefficient Adjustments

For quality assurance of the measured data, Campbell Scientific recommends the coefficient calculations to be adjusted every two years. A returned material authorization (RMA) and completion of the “Declaration of Hazardous Material and Decontamination” form is required. Refer to the *Assistance* page at the end of this manual for more information.

For more information, refer to Appendix A, *Coefficient Calculations* *(p. A-1)*.

Appendix A. Coefficient Calculations

A.1 Basic Measurement Theory

The KH20 uses an empirical relationship between the absorption of the light and the material through which the light travels. This relationship is known as the Beer's law, the Beer-Lambert law, or the Lambert-Beer law. According to the Beer's law, the log of the transmissivity is anti-proportional to the product of the absorption coefficient of the material, k, the distance the light travels, x, and the density of the absorbing material, ρ. The KH20 sensor uses the UV light emitted by the krypton lamp: major line at 123.58 nm and the minor line at 116.49. As the light travels through the air, both the major line and the minor line are absorbed by the water vapor present in the light path. This relationship can be rewritten as follows, where k_w is the absorption coefficient for water vapor, x is the path length for the KH20 sensor, and ρ_w is the water vapor density.

$$T = e^{-k_w x \rho_w} \qquad \text{A-1}$$

If we express the transmissivity, T, in terms of the light intensity before and after passing through the material as measured by the KH20 sensor, V and V_0, respectively, we obtain the following equation.

$$\frac{V}{V_0} = e^{-k_w x \rho_w} \qquad \text{A-2}$$

Taking the natural log of both sides, and solving for the density, ρ_w, yields the following equation.

$$\rho_w = \frac{1}{-k_w x}(\ln V - \ln V_0) \qquad \text{A-3}$$

If the path length, x, and the absorption coefficient for water, k_w are known, it becomes possible to measure the water vapor density ρ_w, by measuring the signal output, V, from KH20.

A.2 Calculation Coefficients for the KH20

To calculate the absorption coefficient of water vapor, k_w, we rewrite the equation A-3, and solve for ln(V).

$$\ln V = -k_w x \rho_w + \ln V_0 \qquad \text{A-4}$$

Equation A-4 shows a linear relationship between the natural log of the KH20 measurement output, $\ln V$, and the water vapor density, ρ_w. FIGURE A-1 shows the plot of the equation A-4 after we ran a KH20 over a full vapor range.

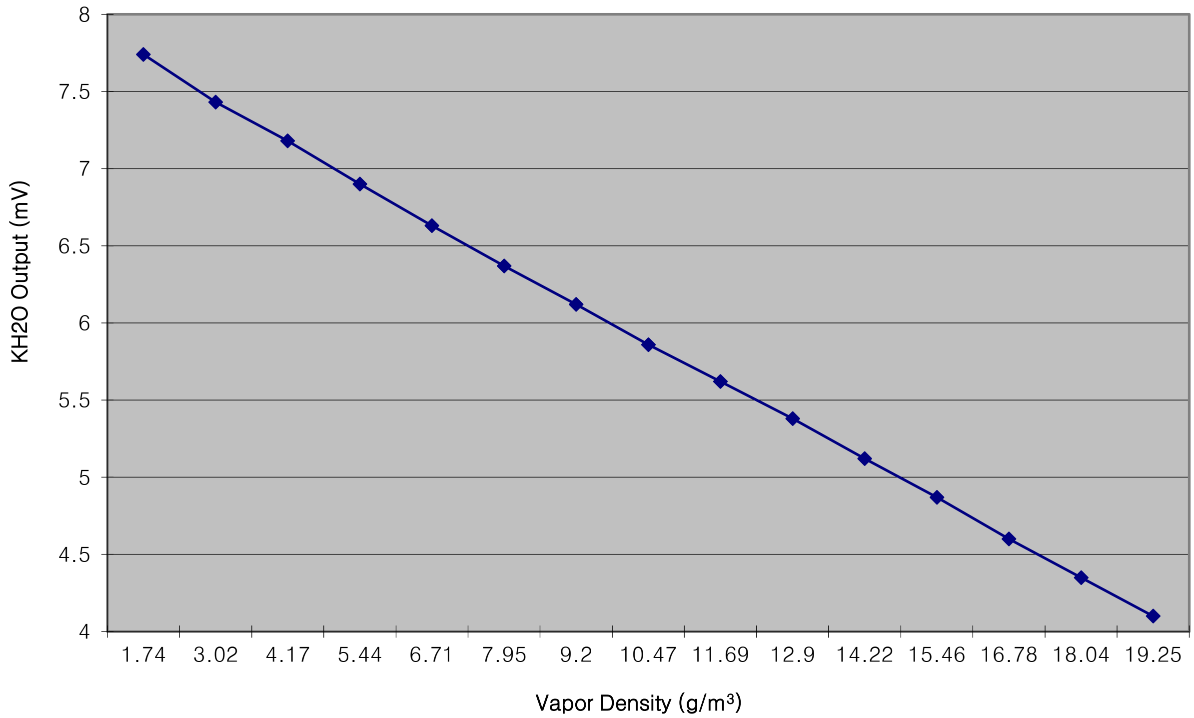

FIGURE A-1. KH20 ln(mV) vs. Vapor Density

We can perform the linear regression on the plot to obtain the slope for the relationship between the ln(mV) and the vapor density. The slope for the graph is the coefficient, $k_w x$. TABLE A-1 shows the result of linear regression analysis. The slope is the product of the absorption coefficient of water vapor, k_w, and the KH20 path length, x.

TABLE A-1. Linear Regression Results for KH20 ln(mV) vs. Vapor Density

Description	Values
Slope (xk_w)	–0.205
Y Intercept ($\ln(V_0)$)	8.033

If we substitute these values, along with the measured lnV into equation A-3, we can obtain the water vapor density, ρ_w. Campbell Scientific performs the calculations twice for each KH20: once with the window cleaned and again with the window scaled. We then break up the vapor density range into dry and wet ranges, and compute the k_w values for each sub range, as well as for the full range. If you know the vapor density range for your site, it is recommended that you select the coefficient, k_w, that is appropriate for your site, the dry range or the wet range. If the vapor range for the site is unknown, or if the vapor range is on the border line between the dry and the wet ranges, use the value for the full range. TABLE A-2 shows the final values the KH20 data report contains. The data shown in TABLE A-2 is from an actual KH20.

TABLE A-2. Final Values for KH20				
	Vapor Range (g/m^3)	**Slope (xk_w)**	**Y Intercept ln (V_0)**	**Coefficient (k_w)**
Full Range	1.74 ~ 19.25	-0.205	3087	-0.144
Dry Range	1.74 ~ 9.20	-0.216	3259	-0.151
Wet Range	7.95 ~ 19.25	-0.201	2899	-0.141

Appendix B. Example Program

The following example program measures the KH20 at 10Hz, and stores the average values into a data table called ‘stats’, as well as the raw data into a data table called ‘ts_data’.

NOTE The KH20 does not monitor absolute water vapor concentration.

CRBasic Example B-1. CR3000 Program to Measure Water Vapor Fluctuations

```
'CR3000 Series Data Logger

'This data logger program measures KH20 Krypton Hygrometer.

'The station operator must enter the constant and the coefficient for the KH20.
'Search for the text string "unique" to find the locations of these constants
'and enter the appropriate values found from the data report of the KH20.

'*** Unit Definitions ***

'Units    Description
'ln_mV    ln(mV)   (natural log of the KH20 millivolts)
'mV       millivolts
'rho_w    g/m^3

'*** Wiring ***

'ANALOG INPUT
'1H    KH20 signal+ (white)
'1L    KH20 signal- (black)
'gnd   KH20 shield (clear)

'EXTERNAL POWER SUPPLY
'POS   KH20 power+ (red)
'      data logger POWER IN 12 (red)
'NEG   KH20 power- (black)
'      KH20 power shield (clear)
'      data logger POWER IN G (black)

PipeLineMode

'*** Constants ***

'Measurement Rate    '10 Hz
Const SCAN_INTERVAL = 100  '100 mSec

'Output period
Const OUTPUT_INTERVAL = 30  'Online flux data output interval in minutes.
Const x = 1            'Unique path length of the KH20 [cm].
Const kw = -0.150      'Unique water vapor absorption coefficient [m^3 / (g cm)].
Const xkw = x*kw       'Path length times water vapor absorption coefficient [m^3 / g].

'*** Variables ***
Public panel_temp
Public batt_volt
Public kh(2)
Public rho_w
Alias kh(1) = kh_mV
Alias kh (2) = ln_kh
Units panel_temp = deg_C
Units batt_volt = volts
Units kh_mV = mV
```

```
Units ln_kh = ln_mV
Units rho_w = g/m^3

'***  Data Output Tables ***
'Processed data
DataTable (stats,True,-1)
  DataInterval (0,OUTPUT_INTERVAL,Min,10)
  Minimum (1,batt_volt,FP2,False,False)
  Average (1,panel_temp,FP2,False)
  Average (2,kh(1),IEEE4,False)
EndTable

'Raw time-series data.
DataTable (ts_data,True,-1)
  DataInterval (0,SCAN_INTERVAL,mSec,100)
  Sample (1,kh_mV,IEEE4)
EndTable

'*** Program ***

BeginProg

  Scan (SCAN_INTERVAL,mSec,3,0)

    'data logger panel temperature.
    PanelTemp (panel_temp,250)

    'Measure battery voltage.
    Battery (batt_volt)

    'Measure KH20.
    VoltDiff (kh_mV,1,mV5000,1,TRUE,200,250,1,0)
    ln_kh = LOG(kh_mV)
    rho_w = ln_kh/xkw

    CallTable stats
    CallTable ts_data

  NextScan
EndProg
```

Appendix C. Equations and Algorithms of Water Vapor Density and Water Flux in KH20 Eddy-Covariance Systems

C.1 Fundamental Equation

A krypton hygrometer (KH20, Campbell Scientific) is a fast-response water vapor analyzer to measure the high-frequency fluctuations of water vapor density in the atmosphere. When the three-dimensional wind speeds are measured nearby using a fast-response sonic anemometer, the fluctuations are used for the eddy-covariance methodology to estimate the water flux (latent heat flux) between ecosystems and the atmosphere.

KH20 has a cylindrical path for measurements (FIGURE 6-1). In the lower end of the path, a krypton lamp emits a major light at 123.58-nm wavelength (wavelength 1) along with a minor light at 116.49-nm wavelength (wavelength 2). The lights penetrate the air along the path length of *x,* in cm, and are received by the detector in the upper end of the path that outputs voltage (V in mV). The lights in both wavelengths are absorbed by two air components: water vapor and oxygen. Without both components along the path, the sensor outputs voltage V_{01} from wavelength 1 and voltage V_{02} from wavelength 2, both of which sum up one voltage output as V_0 ($V_0 = V_{01}+V_{02}$) from the sensor for air free of water vapor and oxygen. Given water vapor density (ρ_w in gH_2O m^{-3}) and oxygen density (ρ_o in gO_2 m^{-3}), based on the Beer–Lambert Law (Wallace and Hobbs. 2006), KH20 output V can be theoretically expressed as:

$$V = V_{01}\exp(-xk_{w1}\rho_w - xk_{o1}\rho_o) + V_{02}\exp(-xk_{w2}\rho_w - xk_{o2}\rho_o) \quad (1)$$

where, on wavelengths 1 and 2, k_{w1} and k_{w2} with subscript w indicating water are the absorption coefficients of water vapor and k_{o1} and k_{o2} with subscript o indicating oxygen are the absorption coefficients of oxygen. Water vapor has similar absorption at both wavelengths (Campbell Scientific Inc. 2010), thus $k_{w1} \approx k_{w2}$ and absorption coefficients of water vapor on both wavelengths could be represented by the same value denoted by k_w in ln(mV) m^3 gH_2O^{-1} cm^{-1}. Similarly, one coefficient also is used by Tanner et al. (1993) and van Dijk et al. (2003) for the absorption by oxygen at both wavelengths. Thus, the absorption coefficients for oxygen on both wavelengths (k_{o1} and k_{o2}) can be represented by the same value denoted by k_o in ln(mV) m^3 gO_2^{-1} cm^{-1}. Further, equation (1) can be solved for ρ_w as:

$$\rho_w = -\frac{1}{xk_w}\ln V + \frac{1}{xk_w}\left(\ln V_0 - xk_o\rho_o\right) \quad (2)$$

This is the fundamental equation for KH20 measurements.

C.2 Working Equation

In the field, KH20 measurements output V values. To acquire ρ_w from fundamental equation (2), other constants (x and V_0), parameters (k_w and k_o), and variable (ρ_o) in this equation are needed. In manufacture process, x is measured in precision and others are statistically estimated in the coefficient calculation process under the background oxygen density (ρ_{oc} in $gO_2\ m^{-3}$). Through the process, the working equation is given

$$\rho_w = -\frac{1}{xk_w}\ln V + \frac{1}{xk_w}\left[C_I + xk_o\left(\rho_{oc} - \frac{C_O M_O P}{R^* T}\right)\right] \tag{3}$$

In this equation, V, P (high-frequency atmospheric pressure in Pa), and T (high-frequency air temperature in K) are variables measured/derived in KH20 eddy-covariance water flux systems; k_w, C_I [termed as "Constant" in ln(mV)], x, and ρ_{oc} are parameters and constants from the coefficient calculation, given in KH20 data report; k_o is 0.00345 ln(mV) $m^3\ g^{-1}\ cm^{-1}$ determined by van Dijk et al (2003) following Tanner et al. (1993) , considered as universal for all KH20 sensors with x around 1.3 cm; C_o is the mole fraction of oxygen that is considered as a constant of 0.2095 in ecosystems (Tanner et al. 1993); M_o is the molar mass of oxygen (32 g $mole^{-1}$); and R^* is universal gas constant (8.3143 J $K^{-1}\ mol^{-1}$).

C.3 Eddy-Covariance Water Flux

Water flux is computed from $\overline{w\rho_w}$ (Webb et al. 1980) where w is vertical wind speed and overbar averages the data over an averaging interval. In practice, it is computed from

$$\overline{w\rho_w} = \overline{w'\rho_w'} + \overline{w}\,\overline{\rho_w} \tag{4}$$

where prime indicates the fluctuation of a given variable away from its mean. In the right side of this equation, the first term is the eddy-covariance term which is the covariance of vertical wind speed with water vapor density and the second term is the WPL term (Webb et al. 1980) which reflects the water flux caused by changes in air density.

Eddy-covariance term is derived from equation (3) as

$$\overline{w'\rho_w'} = -\frac{1}{xk_w}\overline{w'(\ln V)'} + \frac{k_o}{k_w}\frac{C_o M_o \overline{P}}{R^*\overline{T}^2}\overline{w'T'} \tag{5}$$

The second term on the right side of this equation is the oxygen correction term. $\overline{w'T'}$ is temperature flux. It can be directly measured if a fine wiring thermocouple is available; otherwise, it is derived from $\overline{w'T_s'}$ through SND corrections (van Dijk 2002).

The WPL term is given by Webb et al. (1980):

$$\overline{w}\overline{\rho}_w = \mu\sigma\overline{w'\rho_w'} + \left(1+\mu\sigma\right)\frac{\overline{\rho_w}}{\overline{T}}\overline{w'T'} \tag{6}$$

where μ (1.60802) is the ratio of dry air molecular weight (28.97 kg kmol^{-1}) to water molecular weight [18.016 kg kmol^{-1}, page 466 in Wallace and Hobbs (2006)], σ is mean water vapor mass mixing ratio (ratio of mean water vapor to mean dry air density computed in the data processing).

As usual in eddy-covariance measurements, the covariance variables: $\overline{w'\left(\ln V\right)'}$ and $\overline{w'T'}$ need coordinate rotation and frequency corrections. The general algorithm and procedure for coordinate rotation and frequency corrections are addressed in Campbell Scientific Inc (2020), but the equation for frequency response of a KH20 to water vapor density (ln*V*) cannot be found in previous documents from Campbell Scientific.

C.4 Frequency Response of KH20

KH20 measures the water vapor density averaged over a cylindrical light path that has a diameter of 9.5 mm and length of 11 to 15 mm. Andreas (1981) derived the power spectra transfer function for volume averaging [Equation (18) in Andreas (1981)]. His equation includes the first order Bessel function of the first kind that makes the integration of the transfer function over the frequency domain in need of more computation time. Moene (2003) used a simple function to approximate equation (18) of Andreas (1981). Moene's (2003) approximation was developed only for a Krypton Hygrometer with a diameter-ratio of 0.5. Because the cylindrical light path of KH20 for measurements has a fixed diameter, but changeable length, Moene's (2003) approximation only uses the length as a sensor parameter. In his original equation, the approximation curve matches the curve for a diameter-length ratio between 0.5 and 1.0 when the ratio of Kolmogorov microscale (1 mm in the atmosphere) to the path length is 0.014 [Fig. 2 in Andreas (1981)]. Based on the diameter fixed and length range of KH20 cylindrical light path, its diameter-length ratio is about 0.63 to 0.86 within the applicable range of Moene's (2003) approximation for 0.5 to 1.0 as a diameter-length ratio (see page 650). This approximation is given by:

$$T_{\rho_w^2\_VA}(f,x,u) = \exp\left[-2\left(\frac{fx/100}{\overline{u}}\right)^2\right] \tag{7}$$

where f is natural frequency, u is wind speed in the stream-wise direction, and 100 is used to convert x in cm to m. Its application is the same as the power spectral transfer function for line averaging in other Campbell Scientific open-path eddy-covariance systems for the EC155 or IRGASON infrared gas analyzer (Campbell Scientific Inc. 2020)

C.5 References

Andreas, E.L. 1981. The effects of volume averaging on spectra measured with Lyman-Alpha hygrometer. Journal of Applied Meteorology 20: 467-475.

Campbell Scientific Inc. 2010. KH20 Krypton Hygrometer, Logan, UT, US. pp. 10.

Campbell Scientific Inc. 2020. EasyFlux-DL, Logan, UT, US. pp. 10.

Moene, A.F. 2003. Effects of water vapor on the structure parameter of the refractive index for near-infrared radiation. Boundary-Layer Meteorology 107: 635-653.

Tanner, B.D., E. Swiatek, J.P. Greene. 1993. Density fluctuations and use of the krypton Hygrometer in surface flux measurement. Management of Irrigation and Drainage Systems Sponsored by the Irrigation and Drainage Division/ASCE, Park City, Utah.

van Dijk, A. 2002. The Principle of Surface Flux Physics. Research Group of the Royal Netherlands Meteorological Institute and Department of Meteorology and Air Quality with Agricultural University Wageningen. 65p.

van DijK, A, W. Kohsiek, H.A.R. de Bruin. 2003. Oxygen sensitivity of krypton and Lyman-α hygrometers. Journal of Atmospheric and Oceanic Technology 20: 143-151.

Wallace, J.M., P.V. Hobbs. 2006. Atmospheric Science: An Introductory Survey, 2nd edition. Elsevier, Amsterdam. pp: 483.

Webb, E.K., G.I. Pearman, R. Leuning. 1980. Correction of flux measurements for density effects due to heat and water transfer. Quart. J. Met. Soc. 106: 85-100.

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Safety

DANGER — MANY HAZARDS ARE ASSOCIATED WITH INSTALLING, USING, MAINTAINING, AND WORKING ON OR AROUND **TRIPODS, TOWERS, AND ANY ATTACHMENTS TO TRIPODS AND TOWERS SUCH AS SENSORS, CROSSARMS, ENCLOSURES, ANTENNAS, ETC**. FAILURE TO PROPERLY AND COMPLETELY ASSEMBLE, INSTALL, OPERATE, USE, AND MAINTAIN TRIPODS, TOWERS, AND ATTACHMENTS, AND FAILURE TO HEED WARNINGS, INCREASES THE RISK OF DEATH, ACCIDENT, SERIOUS INJURY, PROPERTY DAMAGE, AND PRODUCT FAILURE. TAKE ALL REASONABLE PRECAUTIONS TO AVOID THESE HAZARDS. CHECK WITH YOUR ORGANIZATION'S SAFETY COORDINATOR (OR POLICY) FOR PROCEDURES AND REQUIRED PROTECTIVE EQUIPMENT PRIOR TO PERFORMING ANY WORK.

Use tripods, towers, and attachments to tripods and towers only for purposes for which they are designed. Do not exceed design limits. Be familiar and comply with all instructions provided in product manuals. Manuals are available at www.campbellsci.com. You are responsible for conformance with governing codes and regulations, including safety regulations, and the integrity and location of structures or land to which towers, tripods, and any attachments are attached. Installation sites should be evaluated and approved by a qualified engineer. If questions or concerns arise regarding installation, use, or maintenance of tripods, towers, attachments, or electrical connections, consult with a licensed and qualified engineer or electrician.

General

- Protect from over-voltage.
- Protect electrical equipment from water.
- Protect from electrostatic discharge (ESD).
- Protect from lightning.
- Prior to performing site or installation work, obtain required approvals and permits. Comply with all governing structure-height regulations.
- Use only qualified personnel for installation, use, and maintenance of tripods and towers, and any attachments to tripods and towers. The use of licensed and qualified contractors is highly recommended.
- Read all applicable instructions carefully and understand procedures thoroughly before beginning work.
- Wear a **hardhat** and **eye protection**, and take **other appropriate safety precautions** while working on or around tripods and towers.
- **Do not climb** tripods or towers at any time, and prohibit climbing by other persons. Take reasonable precautions to secure tripod and tower sites from trespassers.
- Use only manufacturer recommended parts, materials, and tools.

Utility and Electrical

- **You can be killed** or sustain serious bodily injury if the tripod, tower, or attachments you are installing, constructing, using, or maintaining, or a tool, stake, or anchor, come in **contact with overhead or underground utility lines**.
- Maintain a distance of at least one-and-one-half times structure height, 6 meters (20 feet), or the distance required by applicable law, **whichever is greater**, between overhead utility lines and the structure (tripod, tower, attachments, or tools).
- Prior to performing site or installation work, inform all utility companies and have all underground utilities marked.
- Comply with all electrical codes. Electrical equipment and related grounding devices should be installed by a licensed and qualified electrician.
- Only use power sources approved for use in the country of installation to power Campbell Scientific devices.

Elevated Work and Weather

- Exercise extreme caution when performing elevated work.
- Use appropriate equipment and safety practices.
- During installation and maintenance, keep tower and tripod sites clear of un-trained or non-essential personnel. Take precautions to prevent elevated tools and objects from dropping.
- Do not perform any work in inclement weather, including wind, rain, snow, lightning, etc.

Maintenance

- Periodically (at least yearly) check for wear and damage, including corrosion, stress cracks, frayed cables, loose cable clamps, cable tightness, etc. and take necessary corrective actions.
- Periodically (at least yearly) check electrical ground connections.

Internal Battery

- Be aware of fire, explosion, and severe-burn hazards.
- Misuse or improper installation of the internal lithium battery can cause severe injury.
- Do not recharge, disassemble, heat above 100 °C (212 °F), solder directly to the cell, incinerate, or expose contents to water. Dispose of spent batteries properly.

WHILE EVERY ATTEMPT IS MADE TO EMBODY THE HIGHEST DEGREE OF SAFETY IN ALL CAMPBELL SCIENTIFIC PRODUCTS, THE CUSTOMER ASSUMES ALL RISK FROM ANY INJURY RESULTING FROM IMPROPER INSTALLATION, USE, OR MAINTENANCE OF TRIPODS, TOWERS, OR ATTACHMENTS TO TRIPODS AND TOWERS SUCH AS SENSORS, CROSSARMS, ENCLOSURES, ANTENNAS, ETC.

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