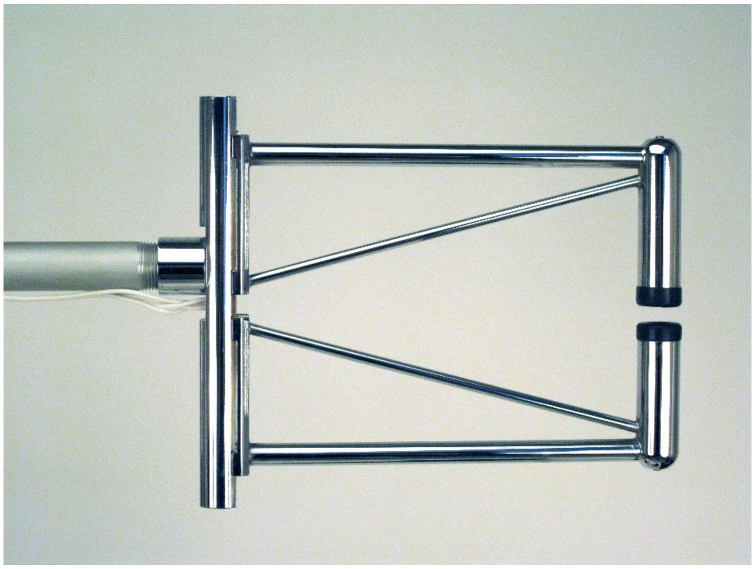
Product Manual

Sensor

KH20

Krypton Hygrometer



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Guarantee

This equipment is guaranteed against defects in materials and workmanship. We will repair or replace products which prove to be defective during the guarantee period as detailed on your invoice, provided they are returned to us prepaid. The guarantee will not apply to:

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- Batteries
- Any product which has been subjected to misuse, neglect, acts of God or damage in transit.

Campbell Scientific will return guaranteed equipment by surface carrier prepaid. Campbell Scientific will not reimburse the claimant for costs incurred in removing and/or reinstalling equipment. This guarantee and the Company's obligation thereunder is in lieu of all other guarantees, expressed or implied, including those of suitability and fitness for a particular purpose. Campbell Scientific is not liable for consequential damage.

Please inform us before returning equipment and obtain a Repair Reference Number whether the repair is under guarantee or not. Please state the faults as clearly as possible, and if the product is out of the guarantee period it should be accompanied by a purchase order. Quotations for repairs can be given on request. It is the policy of Campbell Scientific to protect the health of its employees and provide a safe working environment, in support of this policy a "Declaration of Hazardous Material and Decontamination" form will be issued for completion.

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Note that goods sent air freight are subject to Customs clearance fees which Campbell Scientific will charge to customers. In many cases, these charges are greater than the cost of the repair.

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WHEN MEASUREMENTS MATTER

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PLEASE READ FIRST

About this manual

Please note that this manual was originally produced by Campbell Scientific Inc. primarily for the North American market. Some spellings, weights and measures may reflect this origin.

Some useful conversion factors:

Area: 1 in^2 (square inch) = 645 mm^2

Length: 1 in. (inch) = 25.4 mm
1 ft (foot) = 304.8 mm
1 yard = 0.914 m
1 mile = 1.609 km

Mass: 1 oz. (ounce) = 28.35 g
1 lb (pound weight) = 0.454 kg

Pressure: 1 psi (lb/in^2) = 68.95 mb

Volume: 1 UK pint = 568.3 ml
1 UK gallon = 4.546 litres
1 US gallon = 3.785 litres

In addition, while most of the information in the manual is correct for all countries, certain information is specific to the North American market and so may not be applicable to European users.

Differences include the U.S standard external power supply details where some information (for example the AC transformer input voltage) will not be applicable for British/European use. *Please note, however, that when a power supply adapter is ordered it will be suitable for use in your country.*

Reference to some radio transmitters, digital cell phones and aerials may also not be applicable according to your locality.

Some brackets, shields and enclosure options, including wiring, are not sold as standard items in the European market; in some cases alternatives are offered. Details of the alternatives will be covered in separate manuals.

Part numbers prefixed with a "#" symbol are special order parts for use with non-EU variants or for special installations. Please quote the full part number with the # when ordering.

Recycling information

At the end of this product's life it should not be put in commercial or domestic refuse but sent for recycling. Any batteries contained within the product or used during the products life should be removed from the product and also be sent to an appropriate recycling facility.

Campbell Scientific Ltd can advise on the recycling of the equipment and in some cases arrange collection and the correct disposal of it, although charges may apply for some items or territories.

For further advice or support, please contact Campbell Scientific Ltd, or your local agent.

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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.eu or by telephoning +44(0) 1509 828 888 (UK). 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

- Prior to performing site or installation work, obtain required approvals and permits. Comply with all governing structure-height regulations, such as those of the FAA in the USA.
- 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, or 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.

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.

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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KH20 Krypton Hygrometer

1. Introduction

The KH20 is a highly sensitive hygrometer designed for measurement of rapid fluctuations in atmospheric water vapour, 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 front 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 aluminium 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 vapour 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 vapour, and a small amount of the minor line is absorbed by oxygen. The KH20 is not suitable for absolute water vapour 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, *Calibrating KH20* *(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

Calibration 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 Aluminium 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.

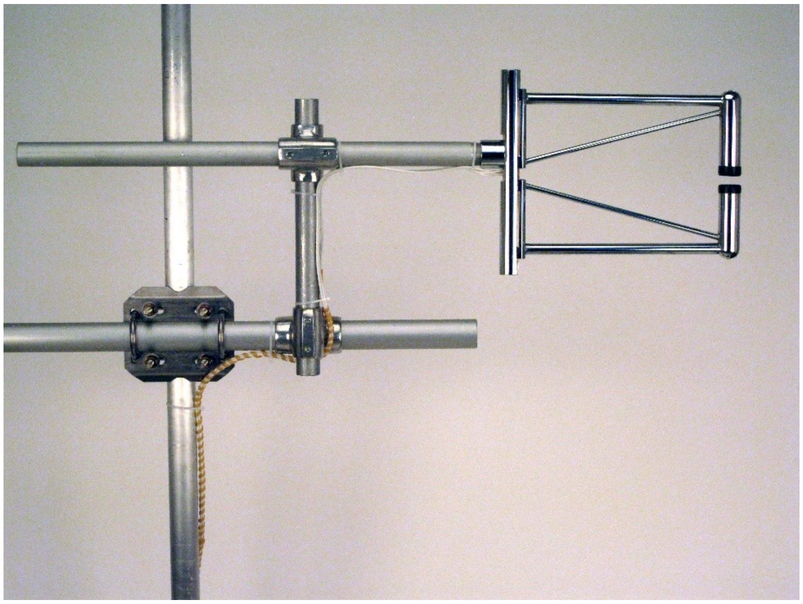

FIGURE 6-1. Mounting KH20 to a tripod.

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 (see FIGURE 6-2). This will provide enough room to attach the connectors to the bottom of the electronics box later.

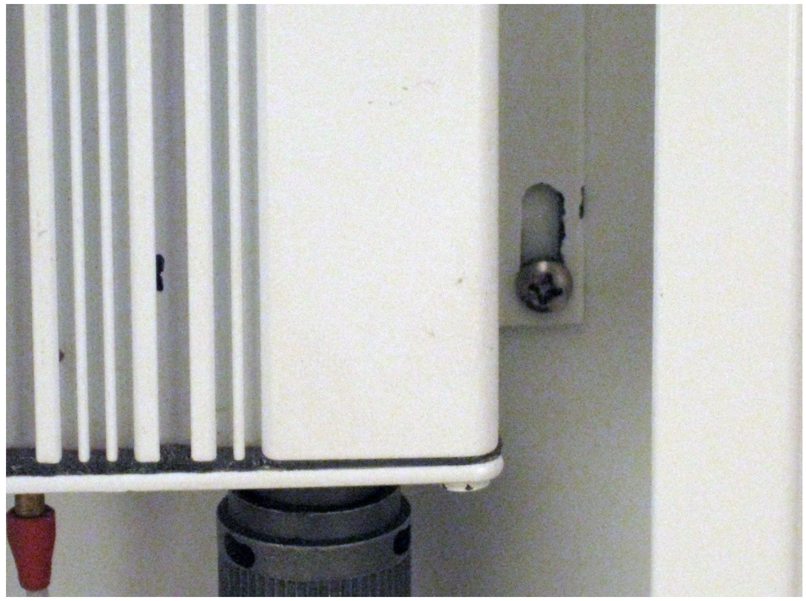

FIGURE 6-2. Proper mounting position of the electronics box.

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 6-3). 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).

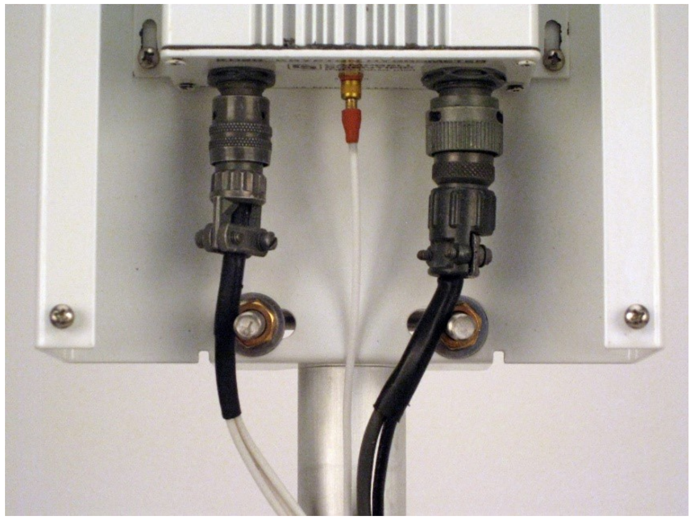

FIGURE 6-3. Attaching cables to the electronics box.

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

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

6.3 Wiring

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

Wire	Wire Label	Data Logger Connection Terminal
White	Signal	**U** configured for differential input[1], **DIFF H** (differential high, analogue-voltage input)
Black (from white/black set)	Signal Reference	**U** configured for differential input[1, 2], **DIFF L** (differential low, analogue-voltage input) [2]
Red	Power 12V	**12V**
Black (from red/black set)	Power Ground	**G**
Clear	Shield	⏚ (analogue 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 analogue 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 KH20 Calibration

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

TABLE 6-2. KH20 Calibration Ranges

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

Before the water vapour 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 vapour range is appropriate for the site?

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

7. Maintenance and Calibration

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-mould 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 discolouration 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 vapour, 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 calibration curve. However, the scaling over a typical flux averaging period is small. Thus, water vapour 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 vapour absorption coefficient for scaled window from the calibration sheet if the window will be allowed to scale during measurements.

7.5 Calibration

For quality assurance of the measured data, Campbell Scientific recommends the KH20 be recalibrated every two years. Calibrations require a returned material authorization (RMA) and completion of the "Declaration of Hazardous Material and Decontamination" form. Refer to the Read First page at the beginning of this manual for more information.

For more information on the calibration process, refer to Appendix A, *Calibrating KH20* *(p. A-1)*.

Appendix A. Calibrating KH20

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 vapour present in the light path. This relationship can be rewritten as follows, where k_w is the absorption coefficient for water vapour, x is the path length for the KH20 sensor, and ρ_w is the water vapour density.

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

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.

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

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

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

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

A.2 Calibration of KH20

The KH20 calibration process is to find the absorption coefficient of water vapour, k_w. To do this, we rewrite the equation A-3, and solve for ln(V).

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

It now becomes obvious from the equation A-4 that there is a linear relationship between the natural log of the KH20 measurement output, $\ln V$, and the water vapour density, ρ_w. FIGURE A-1 shows the plot of the equation A-4 after we ran a KH20 over a full calibration vapour range.

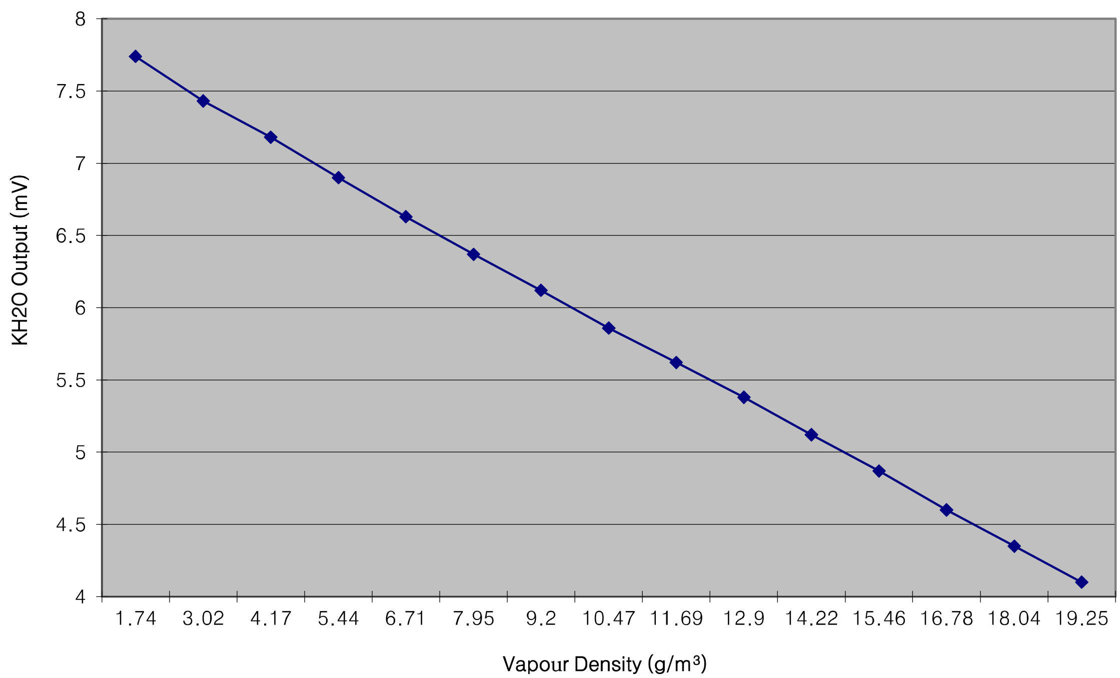

FIGURE A-1. KH20 ln(mV) vs. Vapour Density

We can perform the linear regression on the plot to obtain the slope for the relationship between the ln(mV) and the vapour 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 vapour, k_w, and the KH20 path length, x.

TABLE A-1. Linear Regression Results for KH20 ln(mV) vs. Vapour 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 vapour density, ρ_w. Campbell Scientific performs the calibration twice for each KH20: once with the window cleaned, and again with the window scaled. We then break up the vapour 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 vapour 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 vapour range for the site is unknown, or if the vapour 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 calibration values the KH20 calibration certificate contains. The data shown in TABLE A-2 is from an actual KH20.

TABLE A-2. Final Calibration Values for KH20				
	Vapour 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 vapour concentration.

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

```
'CR3000 Series Data Logger

'This data logger program measures KH20 Krypton Hygrometer.

'The station operator must enter the constant and the calibration value for the KH20.
'Search for the text string "unique" to find the locations of these constants
'and enter the appropriate values found from the calibration sheet 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 vapour absorption coefficient [m^3 / (g cm)].
Const xkw = x*kw            'Path length times water vapour 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 KH2O.
    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. EasyFlux® DL CR6KH20

C.1 Introduction

EasyFlux® DL CR6KH20 is a CRBasic program that enables a CR6 data logger, along with a KH20 and CSAT3B, to collect fully corrected fluxes of latent heat (H_2O), sensible heat, and momentum. The program processes the EC data using commonly used corrections in the scientific literature. The program can also calculate the ground surface heat flux and energy closure by adding an optional suite of energy balance sensors. Because the energy balance sensors require more analogue terminals than the CR6 has, the program supports the addition of a VOLT116 (or CDM-A116) analogue terminal expansion module.

Specifically, the program supports data collection and processing from the following sensors.

REQUIRED SENSORS:

- KH20 Krypton Hygrometer (qty 1)
- CSAT3B Sonic Anemometer (qty 1)
- Temperature/Relative Humidity (RH) Probe (qty 1). Supported Models:
  - HMP155A
  - EE181

OPTIONAL SENSORS:

- CS106 Barometer (qty 0 to 1)
- FW3 Fine Wire Thermocouple (qty 0 to 1)
- GPS16X-HVS GPS Receiver (qty 0 to 1)
- Radiation measurements
  - Option 1
    - NR-LITE2 Net Radiometer (qty 0 to 1)
    - CS301 or CS320 Pyranometer (qty 0 to 1)
    - CS310 Quantum Sensor (qty 0 to 1)
    - SI-111 Infrared Radiometer (qty 0 to 1)
  - Option 2
    - SN500SS, or NR01, or CNR4 4-Way Radiometer (qty 0 to 1; if using CNR4, the CNF4 Ventilation and Heating Unit is also supported)
- TE525MM Rain Gauge (qty 0 to 1)
- TCAV Soil Thermocouple Probe (qty 0 to 3)
- Soil Water Content Reflectometer (qty 0 to 3)
  - CS650
  - CS655
- Soil Heat Flux Plates
  - Option 1: HFP01 plates (qty 0 to 3)
  - Option 2: HFP01SC self-calibrating plates (qty 0 to 3)

NOTE It may be possible to customize the program for other sensors or quantities in configurations not described here. Contact Campbell Scientific for more information.

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NOTE The VOLT116 and CDM-A116 are functionally the same, however their OSes are not interchangeable. If updating an OS, make sure it is for the correct model.

C.2 Precautions

EasyFlux DL CR6KH20 requires the CR6 to have operating system (OS) version 09.02 or newer. If using a VOLT116, it must have OS v.01 or newer, or if using a CDM-A116, it must have v.06 or newer.

The program applies the most common EC corrections to fluxes. However, the user should determine the appropriateness of the corrections for their site.

Campbell Scientific always recommends saving time-series data in the event reprocessing of raw data is warranted. Further, the user should determine the quality and fitness of all data for publication, regardless of whether said data were processed by *EasyFlux DL CR6KH20* or another tool.

As *EasyFlux DL CR6KH20* is not encrypted, users have the ability to view and edit the code. However, Campbell Scientific does not guarantee the function of an altered program.

C.3 Wiring

When wiring the sensors to the data logger or VOLT116, the default wiring schemes, along with the number of instruments *EasyFlux DL CRKH20* supports, should be followed if the standard version of the program is being used. TABLE C-1 through TABLE C-13 present the wiring schemes.

A KH20 and CSAT3B are the only required sensors for the program. The additional sensors described in the following tables are optional, although the CS106 and FW3 are recommended. Many of the optional sensors are wired to a VOLT116 (or CDM-A116) module, which effectively increases the CR6 analogue terminals. If one or more of the optional sensors are not used, the data logger or VOLT116 terminals assigned to those sensor wires should be left unwired.

NOTE If the standard data logger program is modified, the wiring presented in TABLE C-1 may no longer apply. In these cases, refer directly to the program code to determine proper wiring.

NOTE If using an analogue expansion module, all wiring and connections are the same whether using a VOLT116 or a CDM-A116. Therefore, throughout this appendix, the wiring terminals are only listed for the VOLT116.

C.3.1 Required Sensors

A KH20, CSAT3B, and Temp/RH Probe must be wired to the CR6 for *EasyFlux DL CR6KH20* to be functional. TABLE C-1 shows the default wiring for these sensors.

TABLE C-1. Default Wiring for Required Sensors

Sensor	Quantity	Wire Description	Colour	Terminal
KH20	1	Signal	White	U3
		Signal Reference	Black	U4[1/]
		Power	Red	12V
		Power Ground	Black	G (power ground)
		Shield	Clear	⏚ (analogue ground)
CSAT3B	1	CSAT3BCBL3 CPI Cable	RJ45 Connector	CR6 CPI Port (if no Volt116) or Volt116 CPI Port
		CSAT3BCBL2 Power Cable, 12V	Red	12V
		CSAT3BCBL2 Power Cable, Ground	Black	G
HMP155A/*EE181*[2/] Temp/RH Probe	1	Temp Signal	Yellow/*Yellow*	U5
		RH Signal	Blue/*Blue*	U6
		RH Signal Reference	White/*Black*	G[3/]
		Shield	Clear/*Clear*	⏚
		Power	Red/*Red*	+12 V
		Power Ground	Black/*None*	G[3/]

[1/] Wire a user-supplied jumper from U4 to ⏚.

[2/] Wire colours for the HMP155A are shown in normal font, while colours for the EE181 are italicized.

[3/] Due to terminal constraints, the Temp/RH Probe is a single-ended (SE) voltage measurement. As an SE measurement from a sensor that is powered continuously, wire the signal reference and power ground wires both to G.

C.3.2 Optional Sensors

C.3.2.1 VOLT116 Module

Due to the limitations on terminal count of the CR6, a VOLT116 (or CDM-A116) module is required when adding optional sensors. Prepare the module as follows:

1. Connect the module to a 10-32 VDC power source.

2. Launch Campbell Scientific *Device Configuration Utility* software (v2.12 or newer) and select **VOLT116**. If this is the first time connecting, follow the instructions on the main screen to download and install the USB driver to the computer.

3. Select the appropriate COM port and click **Connect**.

4. Once connected, a list of settings is shown. Navigate to ***CPI Address** and* change the value to **1**. Press **Apply** and exit the software.

5. Use an Ethernet cable (included with the module) to connect the module CPI port to the CR6 CPI port.

C.3.2.2 Barometer

A CS106 Barometer is recommended for increased accuracy due to calculations and unit conversions that use ambient pressure. TABLE C-2 shows the default wiring for *EasyFlux DL CR6KH20.*

TABLE C-2. Default Wiring for CS106 Barometer

Sensor	Quantity	Wire Description	Colour	CR6 Terminal
CS106 Barometer	0 or 1	Signal	Blue	U7
		Signal Reference	Yellow	⏚
		Shield	Clear	⏚
		12V	Red	12V
		Power Ground	Black	G
		Trigger (not used)	Green	G

C.3.2.3 Fine Wire Thermocouple

A fine wire thermocouple is recommended for a more accurate and direct measurement of sensible heat flux. If no fine wire thermocouple is used, an estimate of sensible heat flux is still given; it is derived using the covariance of sonic temperature and vertical wind and applying the SND correction. The *EasyFlux DL CR6KH20* can support from zero to one fine-wire thermocouple. Shown in TABLE C-3 are the available types and default wiring for adding a fine-wire thermocouple.

TABLE C-3. Default Wiring for Fine Wire Thermocouple

Sensor	Quantity	Wire Description	Colour	VOLT116 Terminal
FW3 Fine Wire Thermocouple[1/]	0 or 1	Signal	Purple	Diff 15H
		Signal Reference	Red	Diff15L
		Shield	Clear	⏚

[1/] The FW05 and FW1 may be used instead of the FW3, although they are more fragile and may require more frequent replacement.

C.3.2.4 GPS Receiver

A GPS receiver such as the GPS16X-HVS is optional, but will keep the data logger clock synchronized to GPS time. If the CR6 clock differs by one millisecond or more, *EasyFlux DL CR6OP* will resynchronize the data-logger clock to match the GPS. The GPS receiver also calculates solar position. TABLE C-4 shows the default wiring for the GPS16X-HVS.

TABLE C-4. Default Wiring for GPS Receiver

Sensor	Quantity	Wire Description	Colour	CR6 Terminal
GPS16X-HVS	0 or 1	PPS	Grey	U1
		TXD	White	U2
		Shield	Clear	⏚
		12V	Red	12V
		Power Ground	Black	G
		Unused	Yellow and Blue	G

C.3.2.5 Radiation Measurements Option 1

There are two options for making radiation measurements with *EasyFlux DL CR6KH20* . The program can support a combination of the sensors described in TABLE C-5. Alternatively, it can support one of the three types of four-way radiometers described in TABLE C-6. TABLE C-5 gives the default wiring for Option 1. TABLE C-6 shows the details of the default wiring for Option 2.

TABLE C-5. Default Wiring for Radiation Measurement Option 1

Sensor	Quantity	Wire Description	Colour	Terminal
NR-LITE2 Net Radiometer	0 or 1	Radiation Signal	Red	CR6 U8
		Signal Reference	Blue	CR6 ⏚
		Shield	Black	CR6 ⏚
CS301 Pyranometer[1/]	0 or 1	Signal	White	VOLT116 Diff 9H
		Signal Reference	Black	VOLT116 Diff 9L[2/]
		Shield	Clear	VOLT116 ⏚
CS320 Digital Pyranometer[1/]	0 or 1	Signal	White	CR6 U11
		Signal Reference	Blue	CR6 ⏚
		Shield	Clear	CR6 ⏚
		12V Power	Red	CR6 12V
		Power Ground	Black	CR6 G
CS310 Quantum Sensor	0 or 1	Signal	Red	VOLT116 Diff 10H
		Signal Reference	Black	VOLT116 Diff 10L
		Shield	Clear	VOLT116 ⏚

TABLE C-5. Default Wiring for Radiation Measurement Option 1

Sensor	Quantity	Wire Description	Colour	Terminal
SI-111/*SI-111SS* Infrared Radiometer	0 or 1	Target Temp Signal	Red/*White*	VOLT116 Diff 11H
		Target Temp Reference	Black/*Black*	VOLT116 Diff 11L
		Shield	Clear/*Clear*	VOLT116 ⏚
		Sensor Temp Signal	Green/*Green*	VOLT116 Diff 12H
		Sensor Temp Reference	Blue/*Blue*	VOLT116 ⏚
		Voltage Excitation	White/*Red*	VOLT116 X3

[1/]Use only one pyranometer, the CS301 or the CS320. Use the CS320 for applications where a digital, optionally-heated sensor is preferred.

[2/]Jumper to ⏚ with user-supplied wire

C.3.2.6 Radiation Measurements Option 2

Three models of four-way radiometers are compatible with *EasyFlux DL CR6KH20*, however only one may be used at a given time. The default wiring for each of the four-way radiometers is shown in TABLE C-6.

TABLE C-6. Default Wiring for Radiation Measurements Option 2

Sensor	Quantity	Wire Description	Colour	Terminal
SN500SS 4-Way Radiometer	0 or 1	SDI-12 Signal	White	CR6 U11
		Shield	Clear	CR6 ⏚
		Power	Red	CR6 12V
		Power Ground	Black	G
NR01 4-Way Radiometer	0 or 1	Pyranometer Up Signal	Red (cbl 1)	VOLT116 Diff 9H
		Pyranometer Up Reference	Blue[1/] (cbl 1)	VOLT116 Diff 9L[1/]
		Pyranometer Down Signal	White (cbl 1)	VOLT116 Diff 10H
		Pyranometer Down Reference	Green[1/] (cbl 1)	VOLT116 Diff 10L[1/]
		Pyrgeometer Up Signal	Brown (cbl 1)	VOLT116 Diff 11H
		Pyrgeometer Up Reference	Yellow[1/] (cbl 1)	VOLT116 Diff 11L[1/]
		Pyrgeometer Down Signal	Purple (cbl 1)	VOLT116 Diff 12H
		Pyrgeometer Down Reference	Grey[1/] (cbl 1)	VOLT116 Diff 12L[1/]
		PT100 Signal	White (cbl 2)	VOLT116 Diff 4H
		PT100 Reference	Green (cbl 2)	VOLT116 Diff 4L

TABLE C-6. Default Wiring for Radiation Measurements Option 2				
Sensor	**Quantity**	**Wire Description**	**Colour**	**Terminal**
		Current Excite	Red (cbl 2)	VOLT116 X1
		Current Return	Blue (cbl 2)	VOLT116 ⏚
		Shields	Clear	VOLT116 ⏚
CNR4 4-Way Radiometer	0 or 1	Pyranometer Up Signal	Red	VOLT116 Diff 9H
		Pyranometer Up Reference	Blue[1/]	VOLT116 Diff 9L[1/]
		Pyranometer Down Signal	White	VOLT116 Diff 10H
		Pyranometer Down Reference	Black[1/]	VOLT116 Diff 10L[1/]
		Pyrgeometer Up Signal	Grey	VOLT116 Diff 11H
		Pyrgeometer Up Reference	Yellow[1/]	VOLT116 Diff 11L[1/]
		Pyrgeometer Down Signal	Brown	VOLT116 Diff 12H
		Pyrgeometer Down Reference	Green[1/]	VOLT116 Diff 12L[1/]
		Thermistor Signal	White	VOLT116 Diff 4H
		Thermistor V Excite	Red	VOLT116 X1
		Thermistor Reference	Black	VOLT116 ⏚
		Shields	Clear	VOLT116 ⏚
[1/]Jumper to ⏚ with user-supplied wire				

A CNF4 Ventilation and Heater Unit may be used with the CNR4 4-way Radiometer for more accurate radiation measurements. The CNF4 requires a solid state relay to control the ventilator and heater. The A21REL-12 4-Channel Relay Driver, sold separately, is recommended. Install the A21REL-12 inside the system enclosure near the VOLT116 and data logger. TABLE C-7 lists the wiring connections needed to power and control the A21REL-12; a CABLE3CBL-1 or similar 3-conductor 22 AWG cable is recommended for connections from the A21REL-12 to the VOLT116, and a CABLEPCBL-1 or similar 16 AWG 2-conductor power cable is recommended for power connections from the A21REL-12 to system 12V power source. TABLE C-8 lists the wiring for the CNF4.

TABLE C-7. A21REL-12 Wiring

A21REL-12 Terminal	Connecting Terminal	Cable/Wire
+12V	System +12V[1/]	CABLEPCBL-1, red wire
Ground	System GND[1/]	CABLEPCBL-1, black wire
CTRL 1	VOLT116 SW5V #1	CABLE3CBL-1, red wire
CTRL 2	VOLT116 SW5V #2	CABLE3CBL-1, black wire
CTRL 3	VOLT116 SW5V #3	CABLE3CBL-1, white wire

The +12V terminal on the A21REL-12 needs to be in common with the REL 1 COM, REL 2 COM, and REL 3 COM terminals. To do this, use jumper wires to connect the +12V terminal to REL 1 COM, and then REL1 COM to REL 2 COM, and finally REL2 Com to REL 3 COM.

[1/] For the A21REL-12 power connections, connect +12V and G to a system or external power supply. Do not connect to the +12V or G terminals on the CR6 or VOLT116.

TABLE C-8. CNF4 Wiring

Sensor	Quantity	Wire Description	Colour	Terminal
CNF4	0 or 1, only use with a CNR4	Tachometer Output	Green	CR6 U11
		Tachometer Reference	Grey	CR6 ⏚
		Ventilator Power	Yellow	A21REL-12 REL 1 NO
		Ventilator Ground	Brown	A21REL-12 REL G
		Heater #1 Power	White	A21REL-12 REL 2 NO
		Heater #1 Ground	Red	A21REL-12 REL G
		Heater #2 Power	Black	A21REL-12 REL 3 NO
		Heater #2 Ground	Blue	A21REL-12 REL G

C.2.3.7 Precipitation Gauge

EasyFlux DL CR6KH20 can support a single TE525MM tipping rain gauge. The default wiring for the precipitation gauge is shown in TABLE C-9.

TABLE C-9. Default Wiring for Precipitation Gauge				
Sensor	**Quantity**	**Wire Description**	**Colour**	**CR6 Terminal**
TE525MM Tipping Rain Gauge	0 or 1	Pulse Output	Black	U12
		Signal Ground	White	⏚
		Shield	Clear	⏚

C.2.3.8 Soil Temperature

The TCAV is an averaging soil thermocouple probe used for measuring soil temperature. *EasyFlux DL CR6KH20* can support up to three TCAV probes. The order of wiring, however, is important. If only one TCAV sensor is used, it must be wired as described for TCAV #1 in TABLE C-10. A second or third TCAV sensor would be wired according to TCAV #2 or TCAV #3, respectively, in TABLE C-10.

CAUTION If only one TCAV is being used and it is wired according to TCAV #2 or #3, the data logger will not record any TCAV measurements.

TABLE C-10. Default Wiring for Soil Thermocouple Probes				
Sensor	**Quantity**	**Wire Description**	**Colour**	**VOLT116 Terminal**
TCAV #1	1	Signal	Purple	Diff 1H
		Signal Reference	Red	Diff 1L
		Shield	Clear	⏚
TCAV #2	1	Signal	Purple	Diff 2H
		Signal Reference	Red	Diff 2L
		Shield	Clear	⏚
TCAV#3	1	Signal	Purple	Diff 3H
		Signal Reference	Red	Diff 3L
		Shield	Clear	⏚

NOTE The CS650 or CS655 sensors also measure soil temperature. If the CS650 or CS655 sensors are used but no TCAV probes are used, *EasyFlux DL CR6KH20* will use soil temperature from the CS650 or CS655 to compute ground-surface heat flux. If available, soil temperature from the TCAV probe is preferred since it provides a better spatial average. See wiring details for these sensors in TABLE C-11.

C.2.3.9 Soil Water Content

EasyFlux DL CR6KH20 supports one of two models of soil water content sensors: the CS650 or CS655; up to three of one model is supported. A soil water content sensor can also be omitted without affecting function. The default wiring for each is shown in TABLE C-11.

CAUTION If only one soil water content sensor is being used, wire it according to the first probe as described in TABLE C-11. If only one sensor is being used and it is wired according to the second or third sensor, *EasyFlux DL CR6KH20* will not record any measurements from the soil water content sensor.

TABLE C-11. Default Wiring for Soil Water Content Probes

Sensor	Quantity	Wire Description	Colour	CR6 Terminal
CS650/CS655 SDI-12 address 1	1	SDI-12 Data	Green	U9
		SDI-12 Power	Red	+12 V
		SDI-12 Reference	Black	G
		Shield	Clear	G
		Not Used	Orange	⏚
CS650/CS655 SDI-12 address 2	1	SDI-12 Data	Green	U9
		SDI-12 Power	Red	+12 V
		SDI-12 Reference	Black	G
		Shield	Clear	⏚
		Not Used	Orange	G
CS650/CS655 SDI-12 address 3	1	SDI-12 Data	Green	U9
		SDI-12 Power	Red	+12 V
		SDI-12 Reference	Black	G
		Shield	Clear	⏚
		Not Used	Orange	G

C.3.2.10 Soil Heat Flux Plates

EasyFlux DL CR6KH20 can support from zero to soil heat flux plates. The user has the option to use one of two supported models: the HFP01 or HFP01SC (self-calibrating). The default wiring for the HFP01 soil heat flux plates is shown in TABLE C-12, and the default wiring for the HFP01SC plates is shown in TABLE C-13.

TABLE C-12. Default Wiring for Non-Calibrating Soil Heat Flux Plates

Sensor	Quantity	Wire Description	Colour	VOLT116 Terminal
HFP01 #1	1	Signal	White	Diff 5H
		Signal Reference	Green	Diff 5L
		Shield	Clear	⏚

TABLE C-12. Default Wiring for Non-Calibrating Soil Heat Flux Plates				
Sensor	**Quantity**	**Wire Description**	**Colour**	**VOLT116 Terminal**
HFP01 #2	1	Signal	White	Diff 6H
		Signal Reference	Green	Diff 6L
		Shield	Clear	⏚
HFP01 #3	1	Signal	White	Diff 7H
		Signal Reference	Green	Diff 7L
		Shield	Clear	⏚

TABLE C-13. Default Wiring for Soil Heat Flux Plates (Self Calibrating)				
Sensor	**Quantity**	**Wire Description**	**Colour**	**VOLT116 Terminal**
HFP01SC #1	1	Signal	White	Diff 5H
		Signal Reference	Green	Diff 5L
		Shield	Clear	⏚
		Heater Signal	Yellow	Diff 13H
		Heater Reference	Purple	Diff 13L
		Shield	Clear	⏚
		Heater Power	Red	SW12-1[1/]
		Power Reference	Black	G
HFP01SC #2	1	Signal	White	Diff 6H
		Signal Reference	Green	Diff 6L
		Shield	Clear	⏚
		Heater Signal	Yellow	Diff 14H
		Heater Reference	Purple	Diff 14L
		Shield	Clear	⏚
		Heater Power	Red	SW12-1[1/]
		Power Reference	Black	G
HFP01SC #3	1	Signal	White	Diff 7H
		Signal Reference	Green	Diff 7L
		Shield	Clear	⏚
		Heater Signal	Yellow	Diff 16H
		Heater Reference	Purple	Diff 16L
		Shield	Clear	⏚
		Heater Power	Red	SW12-2[1/]
		Power Reference	Black	G
[1/]The SW12 terminals on the VOLT116 are limited to 200mA output. Accordingly, no more than two HFP01SC sensors may be connected to each terminal. Connect heater power wires from HFP01SC #1 and #2 to SW12-1, and connect heater wires from HFP01SC #3 to SW12-2.				

C.4 Operation

Operating *EasyFlux DL CR6KH20* requires the user to enter or edit certain constants and input variables unique to the program or site. Constants are typically edited only once when first initializing the program, whereas site-specific variables are edited upon initial deployment and periodically as site conditions change; for example, canopy height is a variable that may need to be adjusted throughout a growing season. Appendix C.4.1, *Set Constants in CRBasic Editor and Load Program* *(p. C-12)*, provides instructions on setting constants, and Appendix C.4.2, *Enter Site-Specific Variables with Data Logger Keypad or LoggerNet* *(p. C-14)*, provides details on setting variables.

C.4.1 Set Constants in *CRBasic Editor* and Load Program

Before operating the station, the values for configuration constants should be verified in the program code using *CRBasic Editor.*

Open the program in *CRBasic Editor*. After the introductory comments at the top is a section titled “USER-DEFINED CONFIGURATION CONSTANTS” (see FIGURE C-1). Review the constants in this section and modify as needed. If having difficulty locating the correct lines of code, search the program for the word “unique”. This will locate all lines of code containing constants that need to be verified. Look for the text comments on the right side of each line of code for more explanation of the constant. Generally, the constants fall into four categories:

1. **Program Function Constants**
   These are constants that determine the timing of code execution, frequency of writing to output tables, memory allocation, etc. In most cases, the default constants for these values may be retained.

   A program function constant worth mentioning is **ONE_FULL_TABLE**. If this is set to **TRUE**, all of the intermediate and auxiliary measurements will be included as data fields in the main **FLUX_CSFormat** output table, rather than being in a separate output table called **FLUX_NOTES**. For more information, see Appendix C.4.4, *Output Tables* *(p. C-19)*.

2. **Sensor Selection Constants**
   All sensor selection constants begin with the prefix *SENSOR*. The value is set to **TRUE** in the constant table if the system includes the sensor. For example, if a system has a fine-wire thermocouple, the constant **SENSOR_FW** should be set to **TRUE**. When set to **TRUE**, the wiring in TABLE C-13 will apply to the sensor and the data from that sensor will be included in the data output tables.

If a sensor is not used, ensure the constant is set to **FALSE**.

3. **Sensor Quantity Constants**
   The value for these constants indicates the number of each type of sensor in the system. For example, if three soil heat flux (SHF) plates were being used, the constant **NMBR_SHF** would be set to **3**.

4. **Sensor Calibration Constants**
   Some sensors have unique parameters for their measurement

equations; for example, multipliers and/or offsets for linear working equations that are used to convert their raw measurements into the values applicable in analysis. Typically, these parameter values are found on the calibration sheet from the sensor original manufacturer. For example, if an NR-LITE2 net radiometer is being used, a unique multiplier is set in the following line of code: **Constant NRLITE_SENSITIVITY = 16**. The comments in the code explain that the value entered is the sensor sensitivity provided in the NR-LITE2 calibration sheet.

NOTE Constants relating to a particular sensor have been grouped together and have the sensor selection constant at the beginning, such that if the sensor selection constant is set to **FALSE**, the other constants for that sensor may be ignored. For example, the constants dealing with the SI-111SS Infrared Radiometer are grouped together with the **SENSOR_SI111** constant at the top. If a SI-111SS is not being used, **SENSOR_SI111** should be set to **FALSE** and the next five constants dealing with calibration coefficients will be ignored in the program.

After all constants are verified, save the program under a new or modified file name to keep track of different program versions. Finally, send the program to the CR6 using *LoggerNet*, *PC400*, or *PC200W* software.

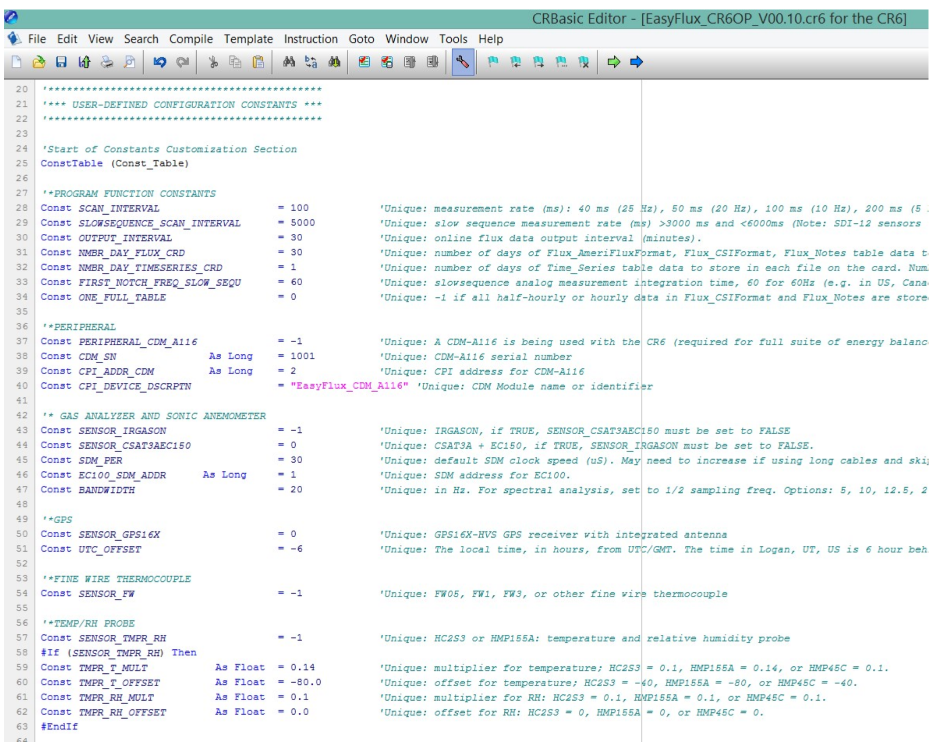

FIGURE C-1. Example screen from CRBasic Editor showing user-defined configuration constants

C.4.2 Enter Site-Specific Variables with Data Logger Keypad or *LoggerNet*

After the eddy-covariance station is installed and the data logger is running the program, connect a CR1000KD Keyboard Display to the CR6 CS-I/O port to view a custom menu of station-specific variables (FIGURE C-2). Use this menu to enter, view, and modify these variables. Use the up and down arrow buttons to navigate to different variables. Press **Enter** to select a variable or to set a new value after typing it. Press **Esc** to return to the previous menu.

FIGURE C-2 depicts the structure of the custom menu. Bypass the custom menu to interact directly with the data logger through the data logger default menus. To bypass the custom menus, select < **System Menu** >. If no CR1000KD is available, these same variables may be viewed and edited using the *LoggerNet* connect screen numeric display of variables from the Public table.

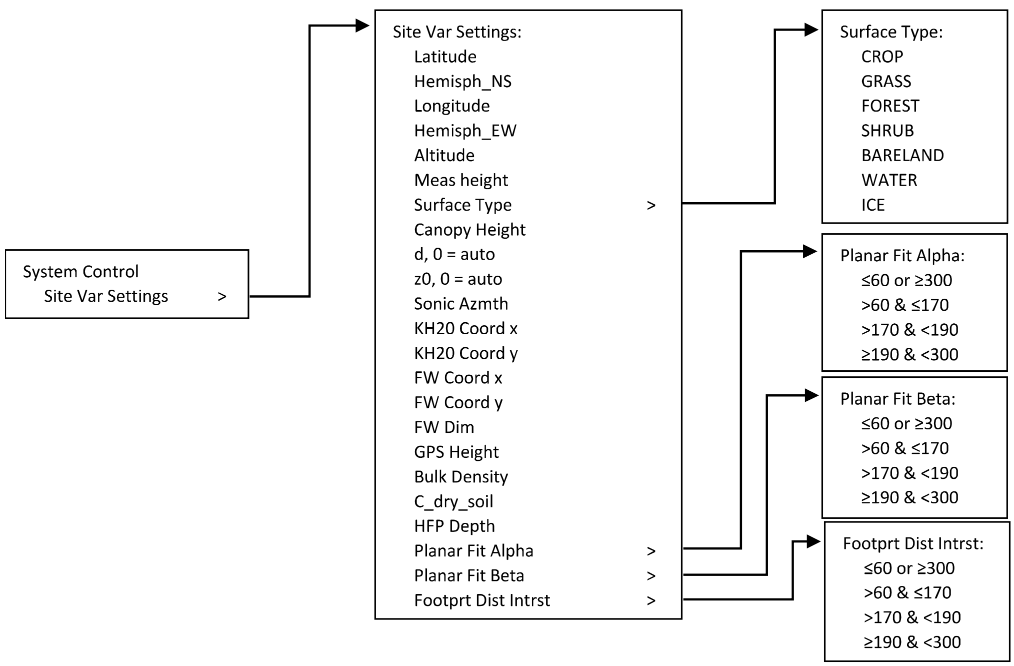

FIGURE C-2. Custom keypad menu; arrows indicate submenus

Before fluxes are processed correctly, the user must go through each of the station variables and set or confirm the assigned values. TABLE C-14 gives short descriptions of each station variable.

TABLE C-14. Station Variables with Descriptions				
Station Variable	**Units**	**Default**	**Description**	**Name of variable in Public Table (in case no CR1000KD available)**
Latitude	decimal degrees	41.766	The site latitude in degrees North or South.	Latitude
Hemisph_NS	none	NORTH	The site latitudinal hemisphere. Options are NORTH or SOUTH.	hemisphere_NS 1 = North –1 = South
Longitude	decimal degrees	111.855	The site longitude in degrees East or West.	Longitude
Hemisph_EW	none	WEST	The site longitudinal hemisphere. Options are EAST or WEST.	hemisphere_EW 1 = East –1 = West
Altitude	m	1356	The site altitude	altitude
Meas Height	m	2	The height of the centre of the eddy-covariance sensor measurement volumes above ground.	height_measurement
Surf Type	none	GRASS	Type of surface at the measurement site. Options are CROP, GRASS, FOREST, SHRUB, BARELAND, and WATER. This is used to estimate displacement height.	surface_type 1 = CROP 2 = GRASS 3 = FOREST 4 = SHRUBLAND 5 = BARELAND 6 = WATER 7 = ICE
Canopy Height	m	0.5	The average height of the canopy.	height_canopy
d	m	0 (Auto)	Displacement height. Set to zero (0) for program to auto-calculate. See the Aerodynamic Height appendix in the *EasyFlux DL CR6OP* manual for details.	displacement_user
z_0	m	0 (Auto)	Roughness length. Set to zero (0) for program to auto-calculate. See the Programmatic Approach appendix in the *EasyFlux DL CR6OP* manual for details.	roughness_user
Sonic Azmth	decimal degrees	0	The compass direction in which the sonic negative x-axis points (the compass direction in which the sonic head is pointing).	sonic_azimuth
KH20 Coord x	m	0.15	Distance along the sonic x-axis between the sonic sampling volume and KH20 sampling volume.	separation_x_kh20

TABLE C-14. Station Variables with Descriptions				
Station Variable	**Units**	**Default**	**Description**	**Name of variable in Public Table (in case no CR1000KD available)**
KH20 Coord y	m	0.15	Distance along the sonic y-axis between the sonic sampling volume and KH20 sampling volume.	separation_y_kh20
FW Coord x	m	0.01227	Distance along the sonic x-axis between the sonic sampling volume and fine-wire thermocouple. If no fine-wire thermocouple is being used, this variable is omitted.	separation_x_FW
FW Coord y	m	-0.02408	Distance along the sonic y-axis between the sonic sampling volume and the fine-wire thermocouple. If no fine-wire thermocouple is being used, this variable is omitted.	separation_y_FW
FW Dim	m	FW3_DIA	Identifies which fine-wire thermocouple is being used and loads the appropriate diameter. For FW05_DIA, FW1_DIA and FW3_DIA, the diameters are 1.27×10^{-5}, 2.54×10^{-5}, and 7.62×10^{-5} m, respectively. If no fine-wire thermocouple is being used, this variable is omitted.	FW_diameter
GPS Height	m	2	The height of the GPS reciever above the ground surface. If GPS is not used, this variable is omitted.	height_GPS16X
Bulk Density	$kg \cdot m^{-3}$	1300	Average bulk density of soil. If energy balance sensors are not used, this variable is omitted.	soil_bulk_density
C_dry_soil	$J \cdot kg^{-1} K^{-1}$	870	Specific heat of dry mineral soil. If energy balance sensors are not used, this variable is omitted.	cds
HFP Depth	m	0.16	Depth of the soil heat flux plates. If energy balance sensors are not used, this variable is omitted.	thick_abv_HFP
Planar Fit Alpha: ≤ 60 or ≥ 300	decimal degrees	0	Alpha angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 0 to 60 and 300 to 360 degrees in the sonic coordinate system (wind blowing into sonic head).[1/]	alpha_PF_60_300

TABLE C-14. Station Variables with Descriptions

Station Variable		Units	Default	Description	Name of variable in Public Table (in case no CR1000KD available)
Planar Fit Alpha	> 60 & ≤ 170	decimal degrees	0	Alpha angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 60 to 170 degrees in the sonic coordinate system (wind blowing from the sector left and behind sonic head).[1/]	alpha_PF_60_170
Planar Fit Alpha	> 170 & < 190	decimal degrees	0	Alpha angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 170 to 190 degrees in the sonic coordinate system (wind blowing from behind sonic head).[1/]	alpha_PF_170_190
Planar Fit Alpha	≥ 190 & < 300	decimal degrees	0	Alpha angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 190 to 300 degrees in the sonic coordinate system (wind blowing from the sector right and behind sonic head).[1/]	alpha_PF_190_300
Planar Fit Beta	≤ 60 or ≥ 300	decimal degrees	0	Beta angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 0 to 60 and 300 to 360 degrees in the sonic coordinate system (wind blowing into sonic head).[1/]	beta_PF_60_300
Planar Fit Beta	> 60 & ≤ 170	decimal degrees	0	Beta angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 60 to 170 degrees in the sonic coordinate system (wind blowing from left and behind sonic head).[1/]	beta_PF_60_170
Planar Fit Beta	> 170 & < 190	decimal degrees	0	Beta angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 170 to 190 degrees in the sonic coordinate system (wind blowing from behind sonic head).[1/]	beta_PF_170_190

TABLE C-14. Station Variables with Descriptions					
Station Variable		**Units**	**Default**	**Description**	**Name of variable in Public Table (in case no CR1000KD available)**
Planar Fit Beta	≥ 190 & < 300	decimal degrees	0	Beta angle used to rotate the wind when the mean horizontal wind is blowing from the sector of 190 to 300 degrees in the sonic coordinate system (wind blowing from right and behind sonic head).[1/]	beta_PF_190_300
Footprint Dist of Interest	≤ 60 or ≥ 300	m	100*z*	The upwind distance of interest from the station when the mean horizontal wind is blowing from the sector of 0 to 60 and 300 to 360 degrees in the sonic coordinate system (wind blowing into sonic head). Note: The program will report the percentage of cumulative footprint from within this distance. The default value is 100 times the aerodynamic height, *z*. Recall that *z* is the difference between the measurement height and displacement height.	dist_intrst_60_300
Footprint Dist of Interest	> 60 & ≤ 170	m	100*z*	The upwind distance of interest from the station when the mean horizontal wind is blowing from the sector of 60 to 170 degrees in the sonic coordinate system (wind blowing from left and behind sonic head).	dist_intrst_60_170
Footprint Dist of Interest	> 170 & < 190	m	100*z*	The upwind distance of interest from the station when the mean horizontal wind is blowing from the sector of 170 to 190 degrees in the sonic coordinate system (wind blowing from behind sonic head).	dist_instrst_170_190
Footprint Dist of Interest	≥ 190 & < 300	m	100*z*	The upwind distance of interest from the station when the mean horizontal wind is blowing from the sector of 190 to 300 degrees in the sonic coordinate system (wind blowing from right and behind sonic head).	dist_intrst_190_300

[1/] Leave *all* planar fit alpha and beta angles set to 0 to use Tanner and Thurtell (1969) method of double coordinate rotations.

NOTE The CSAT3B offers a user-enabled correction for transducer wind shadowing. The correction is disabled as a default state but may be enabled by connecting the CSAT3B to a computer using the CSAT3B USB Data Cable, launching the Device Configuration Utility, and changing the setting for correction. For more information on the correction, see the CSAT3B manual.

C.4.3 Data Retrieval

The program stores a limited amount of data to the internal CPU of the data logger, so a microSD Flash card should be used with the CR6. TABLE C-15 shows the number of days of data a 2 GB, 8 GB, and 16 GB card will typically hold before the memory is full and data starts to be overwritten. In cases where real-time remote monitoring is desired, various telemetry options (for example, cellular, radio, etc.) are available to transmit the processed flux data. Certain conditions may also allow remote transmittal of time series data. Contact Campbell Scientific for more details.

TABLE C-15. microSD Flash Card Fill Times with 10Hz Measurement Rate

microSD Flash card size	Fill time with required sensors only	Fill time with required sensors, FW, CS106, and biomet/energy balance sensors)[1/]
2 GB	~41 days	~35 days
8 GB	~170 days	~141 days
16 GB	~339 days	~281 days

[1/]Biomet and energy balance sensors used for this fill time estimate include the following: NR-LITE2, CS301, CS310, SI-111, TE525MM, TCAV (qty 3), CS616 (qty 3), and HFP01 (qty 3)

NOTE microSD Flash cards from various manufacturers may have slightly different memory sizes on their 2 GB, 8 GB, and 16 GB cards, respectively. Also, as a card ages some of its sectors may become unusable, decreasing the available memory. Fill time estimates given in TABLE C-15 are approximations for new cards.

CAUTION Campbell Scientific recommends and supports only the use of microSD cards obtained from Campbell Scientific. These cards are industrial grade and have passed Campbell Scientific hardware testing. Use of consumer grade cards substantially increases the risk of data loss.

C.4.4 Output Tables

Besides the standard **Public**, **Status**, and **TableInfo** tables that every data logger reports, the program has six output tables. TABLE C-16 gives the names of these output tables, along with a short description, the frequency at which a record is written to the table, and the amount of memory allocated from the CPU and microSD card for each table.

NOTE The variable naming conventions used by AmeriFlux and other flux networks have been adopted in *EasyFlux DL CR6KH20*. Additionally, an output table called **Flux_AmeriFluxFormat** reports the variables in the order and format prescribed by AmeriFlux (see *https://ameriflux.lbl.gov/data/aboutdata/data-variables/*).

If the user would prefer to have the data fields contained in the **Flux_Notes** table appended to the end of the **Flux_CSFormat** table rather than being placed in a separate output table, this is possible by changing the constant **ONE_FULL_TABLE** from **FALSE** to **TRUE** (see Appendix C.4.1, *Set Constants in CRBasic Editor and Load Program* *(p. C-12)*, on changing constants).

TABLE C-16. Data Output Tables

Table Name	Description	Recording Interval	Memory on CR6 CPU	Memory on microSD Card
Time_Series	Time series data (aligned to account for electronic delays)	SCAN_INTERVAL (default 100 ms)	Auto-Allocate (typically less than 1 hour)	See TABLE C-15 for total days. Data broken into daily files.
Diagnostic	Reports most recent diagnostic flags from select sensors	SLW_SCN_INTV (default 6 s)	1 record (most recent scan)	0 records
Monitor_CSAT3B	Reports roll and pitch of the CSAT3B, as well as temp & RH in CSAT3B sensor housing	SLW_SCN_INTV (default 6 s)	1 day	See TABLE C-15 for total days. Data broken into 30-day files.
Flux_AmeriFluxFormat	Processed flux and statistical data following reporting conventions and order of AmeriFlux	OUTPUT_INTERVAL (default 30 minutes)	7 days	See TABLE C-15 for total days. Data broken into 30-day files.
Flux_CSFormat	Processed flux and statistical data	OUTPUT_INTERVAL (default 30 minutes)	7 days	See TABLE C-15 for total days. Data broken into 30-day files.
Flux_Notes	Intermediate variables, station constants, and correction variables used to generate flux results	OUTPUT_INTERVAL (default 30 minutes)	NUM_DAY_CPU (default 7 days)	See TABLE C-15 for total days. Data broken into 30-day files.

TABLE C-16 through TABLE C-22 give a description of all data fields found in each data output table and when each data field is included in the table.

NOTE Prior to coordinate rotations, the orthogonal wind components from the sonic anemometer are denoted as U_x, U_y, and U_z. Following coordinate rotations, the common denotation of u, v, and w is used, respectively.

NOTE Variables with _R denote that the value was computed after coordinate rotations were done. Variables with a _F denote that the value was calculated after frequency corrections were applied. Similarly, _SND and _WPL refer to variables that have had the SND correction or the WPL correction applied, respectively.

TABLE C-17. Data Fields in the Time_Series Data Output Table

Data Field Name	Units	Description	Data Field Included
Ux	$m\cdot s^{-1}$	Wind speed along sonic x-axis	Always
Uy	$m\cdot s^{-1}$	Wind speed along sonic y-axis	Always
Uz	$m\cdot s^{-1}$	Wind speed along sonic z-axis	Always
T_SONIC	deg C	Sonic temperature	Always
diag_sonic	none	Raw sonic diagnostic value (0 indicates no diagnostic flags set)	Always
volt_KH20	mV	Raw signal voltage from KH20	Always
diag_KH20	none	Diagnostic value from KH20 (a non-zero result indicates volt_KH20 was returned as not a number, less than -10 mV, or greater than 4500 mV).	Always
PA	kPa	Ambient pressure	Always
TA_1_1_1	deg C	Air temperature measured by the temp/RH probe	Always
RH_1_1_1	%	Relative humidity measured by the temp/RH probe	Always
FW	deg C	Air temperature measured by fine-wire thermocouple	If FW05, FW1, or FW3 is used

TABLE C-18. Data Fields in the Diagnostic Output Table		
Data Field Name	**Description**	**Data Field Included**
sonic_amp_l_f	Amplitude low diagnostic flag	Always
sonic_amp_h_f	Amplitude high diagnostic flag	Always
sonic_sig_lck_f	Signal lock diagnostic flag	Always
sonic_del_T_f_f	Delta Temp diagnostic flag	Always
sonic_aq_sig_f	Acquiring signal diagnostic flag	Always
sonic_low_volt_f	Low voltage diagnostic flag	Always
sonic_trig_f	No measurement trigger diagnostic flag	Always
sonic_intrnl_hmdty	High internal humidity diagnostic flag	Always
sonic_cal_err_f	Calibration error diagnostic flag	Always
diag_kh20_f	KH20 diagnostic flag	Always
shfp_cal_fail_x_1_1	HFP01SC calibration error flag. Set to true if the calibration multiplier is returned as a non-number or if the calibrated sensitivity it not within 80%-105% of the original sensitivity; x is an index identifying the HFP01SC of concern.	If HFP01SC used

TABLE C-19. Data Fields in the Monitor_CSAT3B Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
board_temp_sonic	deg C	Average temperature of the CSAT3B sensor housing	Always
board_RH_sonic	%	Average relative humidity inside the CSAT3B sensor housing	Always
pitch_sonic	decimal deg	Degrees between horizontal plane and CSAT3B x-axis	Always
roll_sonic	decimal deg	Degrees between horizontal plane and CSAT3B y-axis	Always

TABLE C-20. Data Fields in the Flux_AmeriFluxFormat Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
TIMESTAMP_START	YYYYMMDDHHMM	Start time of the averaging period	Always
TIMESTAMP_END	YYYYMMDDHHMM	End time of the averaging period	Always
H2O	$mmol \cdot mol^{-1}$	Average H_2O molar mixing ratio (dry basis)	Always
H2O_SIGMA	$mmol \cdot mol^{-1}$	Standard deviation of H_2O	Always
LE	$W \cdot m^{-2}$	Latent heat flux after corrections	Always

TABLE C-20. Data Fields in the Flux_AmeriFluxFormat Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
LE_SSITC_TEST	none	Result of steady state and integral turbulence characteristics for LE according to Foken et al. (2004)	Always
ET	$mm \cdot hour^{-1}$	Evapotranspiration	Always
ET_SSITC_TEST	none	Result of steady state and integral turbulence characteristics for ET according to Foken et al. (2004)	Always
H	$W \cdot m^{-2}$	Sensible heat flux after corrections	Always
H_SSITC_TEST	none	Result of steady state and integral turbulence characteristics for FC according to Foken et al. (2004)	Always
G	$W \cdot m^{-2}$	Calculated heat flux at the ground surface	If energy balance sensors used
SG	$W \cdot m^{-2}$	The change in heat storage in the soil above the soil heat flux plates during the averaging interval	If energy balance sensors used
FETCH_MAX	m	Distance upwind where the maximum contribution to the footprint is found	Always
FETCH_90	m	Upwind distance that contains 90% of cumulative footprint. If NAN is returned, integration of the model never reached 90% within the allowable distance of integration. See the Footprint appendix in the *EasyFlux DL CR6OP* manual for more details.	Always
FETCH_55	m	Upwind distance that contains 55% of footprint	Always
FETCH_40	M	Upwind distance that contains 40% of footprint.	Always
WD	decimal degrees	Average wind direction	Always
WS	$m \cdot s^{-1}$	Average wind speed	Always
WS_MAX	$m \cdot s^{-1}$	Maximum wind speed	Always
USTAR	$m \cdot s^{-1}$	Friction velocity	Always
ZL	none	Stability	Always
TAU	$kg \cdot m^{-1} \cdot s^{-2}$	Momentum Flux	Always
TAU_SSITC_TEST	none	Result of steady state and integral turbulence characteristics for FC according to Foken et al. (2004)	Always
MO_LENGTH	M	Monin-Obukhov length	Always
U	$m \cdot s^{-1}$	Average streamwise wind	Always

TABLE C-20. Data Fields in the Flux_AmeriFluxFormat Output Table

Data Field Name	Units	Description	Data Field Included
U_SIGMA	$m \cdot s^{-1}$	Standard deviation of streamwise wind	Always
V	$m \cdot s^{-1}$	Average crosswind	Always
V_SIGMA	$m \cdot s^{-1}$	Standard deviation of crosswind	Always
W	$m \cdot s^{-1}$	Average vertical wind	Always
W_SIGMA	$m \cdot s^{-1}$	Standard deviation of vertical wind	Always
PA	kPa	Atmospheric Pressure	Always
TA_1_1_1	deg C	Air temperature from temp/RH probe	Always
RH_1_1_1	%	Relative humidity from temp/RH probe	Always
T_DP_1_1_1	deg C	Dewpoint temperature from temp/RH probe	Always
VPD	hPa	Vapour pressure deficit	Always
T_SONIC	deg C	Average sonic temperature	Always
T_SONIC_SIGMA	deg C	Standard deviation of sonic temperature	Always
PBLH	m	Estimated planetary boundary layer height	Always
SWC_x_1_1	%	Soil water content. x is an index for the number of soil sensors.	If CS65X used
TS_x_1_1	deg C	Soil temperature. x is an index for the number of soil temperature measurements made.	If TCAV or CS65X used.
ALB	none	Albedo	If SN500SS, NR01, or CNR4 used
NETRAD	$W \cdot m^{-2}$	Net radiation	If SN500SS, NR01, CNR4, or NRlit2 used
PPFD_IN	$\mu mol \cdot m^{-2} \cdot s^{-1}$	Photosynthetic photon density	If CS310 used
SW_IN	$W \cdot m^{-2}$	Incoming shortwave radiation	If SN500SS, NR01, CNR4, CS301, or CS320 used
SW_OUT	$W \cdot m^{-2}$	Outgoing shortwave radiation	If SN500SS, NR01, or CNR4 used
LW_IN	$W \cdot m^{-2}$	Incoming longwave radiation	If SN500SS, NR01, or CNR4 used
LW_OUT	$W \cdot m^{-2}$	Outgoing longwave radiation	If SN500SS, NR01, or CNR4 used
P	mm	Precipitation in output interval	If TE525 used
T_CANOPY	deg C	Canopy temperature	If SI111 used

TABLE C-21. Data Fields in the Flux_CSFormat Data Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
LE	$W \cdot m^{-2}$	Final corrected latent heat flux	Always
LE_QC	grade	Overall quality grade for LE following Foken et al. 2012	Always
LE_samples	count	The total number of time series samples used in calculation of LE	Always
H	$W \cdot m^{-2}$	Final corrected sensible heat flux derived from sonic sensible heat flux	Always
H_QC	grade	Overall quality grade for Hs following Foken et al. 2012	Always
H_samples	count	The total number of time series samples used in calculation of H	Always
H_FW	$W \cdot m^{-2}$	Final corrected sensible heat flux derived from fine-wire thermocouple measurements	If FW05, FW1, or FW3 is used
H_FW_samples	count	The total number of time series samples used in calculation of H_FW	If FW05, FW1, or FW3 is used
NETRAD	$W \cdot m^{-2}$	Average net radiation (corrected for wind)	If NR-LITE2, SN500SS, NR01, or CNR4 used
G	$W \cdot m^{-2}$	Heat flux at the ground surface	If energy balance sensors are used
SG	$W \cdot m^{-2}$	The change in heat storage in the soil above the soil heat flux plates during the averaging interval	If energy balance sensors used
energy_closure	fraction	The ratio of sensible and latent heat fluxes to surface heat flux plus net radiation	If energy balance sensors are used
poor_enrg_clsur	none	If **TRUE**, despite favourable meteorological conditions (adequate turbulence and no rainfall), energy closure is poor. Check instruments.	If energy balance sensors and TE525 used
Bowen_ratio	fraction	The ratio of final sensible heat flux over final latent heat flux	Always
TAU	$kg \cdot m^{-1} \cdot s^{-2}$	Final corrected momentum flux	Always
TAU_QC	grade	Overall quality grade for tau following Foken et al. 2012	Always
USTAR	$m \cdot s^{-1}$	Friction velocity after coordinate rotations and frequency corrections	Always

TABLE C-21. Data Fields in the Flux_CSFormat Data Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
TSTAR	deg C	Scaling temperature after coordinate rotations, frequency corrections, and SDN correction	Always
TKE	$m^2 \cdot s^{-2}$	Specific turbulence kinetic energy after coordinate rotations	Always
TA_1_1_1	deg C	Average ambient temperature from temp/RH probe	Always
RH_1_1_1	deg C	Relative humidity from temp/RH probe	Always
T_DP_1_1_1	deg C	Average dewpoint temperature from temp/RH probe	Always
e	kPa	Average water vapour pressure calculated from temp/RH probe and pressure (from CS106 if used)	Always
e_sat	kPa	Average saturated water vapour pressure calculated from temp/RH probe and pressure (from CS106 if used)	Always
PA	kPa	Average ambient air pressure from CS106 if used, otherwise the nominal air pressure entered by user	Always
VPD	kPa	Vapour pressure deficit	Always
Ux	$m \cdot s^{-1}$	Average U_x	Always
Ux_SIGMA	$m \cdot s^{-1}$	Standard deviation of U_x	Always
Uy	$m \cdot s^{-1}$	Average U_y	Always
Uy_SIGMA	$m \cdot s^{-1}$	Standard deviation of U_y	Always
Uz	$m \cdot s^{-1}$	Average U_z	Always
Uz_SIGMA	$m \cdot s^{-1}$	Standard deviation of U_z	Always
T_SONIC	deg C	Average sonic temperature	Always
T_SONIC_SIGMA	deg C	Standard deviation of sonic temperature	Always
sonic_azimuth	decimal degrees	Compass direction in which the sonic negative x-axis points	Always
WS	$m \cdot s^{-1}$	Average wind speed	Always
WS_RSLT	$m \cdot s^{-1}$	Average horizontal wind speed	Always
WD_SONIC	decimal degrees	Average wind direction in the sonic coordinate system	Always
WD_SIGMA	decimal degrees	Standard deviation of wind direction	Always
WD	decimal degrees	Average compass wind direction	Always
WS_MAX	$m \cdot s^{-1}$	Maximum wind speed	Always
H2O_density	$mmol \cdot mol^{-1}$	Water vapour mass density	Always

TABLE C-21. Data Fields in the Flux_CSFormat Data Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
H2O_density_SIGMA	mmol·mol^{-1}	Standard deviation of water vapour mass density	Always
FW	deg C	Average fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used
FW_SIGMA	deg C	Standard deviation of fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used
P	mm	Total precipitation	If TE525MM is used
NETRAD_meas	W·m^{-2}	Average net radiation (raw, not corrected for wind)	If NR-LITE2 is used
ALB	none	Average albedo	If SN500SS, NR01, or CNR4 used
SW_IN	W·m^{-2}	Average incoming short wave radiation	If SN500SS, NR01, CNR4, CS301, or CS320 used
SW_OUT	W·m^{-2}	Average outgoing short wave radiation	If SN500SS, NR01, or CNR4 used
LW_IN	W·m^{-2}	Average incoming long wave radiation	If SN500SS, NR01, or CNR4 used
LW_OUT	W·m^{-2}	Average outgoing long wave radiation	If SN500SS, NR01, or CNR4 used
T_nr	K	Average sensor body temperature	If NR01 or CNR4 used
T_nr_in	K	Average body temperature of top of sensor	If SN500SS used
T_nr_out	K	Average body temperature of bottom of sensor	If SN500SS used
LW_in_meas	W·m^{-2}	Average raw incoming long wave radiation (not corrected for temperature)	If NR01 or CNR4 used
LW_out_meas	W·m^{-2}	Average raw outgoing long wave radiation (not corrected for temperature)	If NR01 or CNR4 used
PPFD_IN	µmol·s^{-1}·m^{-2}	Average density of photosynthetic active radiation	If CS310 used
sun_azimuth	decimal degrees	Solar azimuth	Always

TABLE C-21. Data Fields in the Flux_CSFormat Data Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
sun_elevation	decimal degrees	Solar elevation	Always
hour_angle	decimal degrees	Solar hour angle	Always
sun_declination	decimal degrees	Solar declination	Always
air_mass_coeff	none	Air mass coefficient: Ratio of the path length between the current solar position to the solar noon	Always
daytime	fraction	Day time in fraction of an output interval	Always
T_CANOPY	deg C	Average temperature of targeted object	If SI111 is used
T_SI111_body	deg C	Average temperature of sensor body	If SI111 is used
TS_x_1_1	deg C	Average soil temperature for each sensor; x is an index for the number of sensors. If both TCAV and CS65X used, this data field defaults to TCAV, and C65X data is stored in TS_CS65X_x_1_1.	If TCAV, CS650, or CS655 used
SWC_x_1_1	$m^3 \cdot m^{-3}$	Average volumetric soil water content for each CS650 or CS655; x is an index for the number of sensors.	If CS650 or CS655 used
TS_CS65X_x_1_1	deg C	Average soil temperature from CS65X probe; x is an index for the number of sensors.	If TCAV and CS65X used
CS65X_EC_x_1_1	$dS \cdot m^{-1}$	Average electrical conductivity for each sensor; x is an index for the number of CS650 or CS655	If CS650 or CS655 used
G_plate_x_1_1	$W \cdot m^{-2}$	Average soil heat flux at plate; x is an index for the number of HFP01 or HFP01SC	If HFP01 or HFP01SC used
G_x_1_1	$W \cdot m^{-2}$	Average heat flux at ground surface; x is an index for each soil sensor suite replicate (suite includes soil temperature, soil water content, and soil heat flux)	If HFP01 or HFP01SC, TCAV, and CS65X used
SG_x_1_1	$W\ m^{-2}$	Heat flux manifested as heat storage in layer between heat flux plate and soil surface; x is an index for the number of soil temp and water content sensor pairs.	If CS65X, or TCAV and CS65X, used
FETCH_MAX	m	Distance upwind where the maximum contribution to the footprint is found	Always
FETCH_90	m	Upwind distance that contains 90% of cumulative footprint	Always

TABLE C-21. Data Fields in the Flux_CSFormat Data Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
FETCH_55	m	Upwind distance that contains 55% of footprint	Always
FETCH_40	m	Upwind distance that contains 40% of footprint. If **NAN** is returned, integration of the model never reached 90% within the allowable distance of integration. See the Footprint appendix in the *EasyFlux DL CR6OP* manual for more details.	Always
UPWND_DIST_INTRST	m	Upwind distance of interest for the average wind direction	Always
FP_DIST_INTRST	%	Percentage of footprint from within the upwind range of interest	Always
FP_EQUATION	text	Returns either **Kljun** or **KormannMeixner**; the model of Kljun et al. (2004) is used for applicable atmospheric conditions, else the model of Kormann & Meixner (2001) is used	Always

TABLE C-22. Data Fields in the Flux_Notes Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
UxUy_cov	$m^2 \cdot s^{-2}$	Covariance of U_x and U_y	Always
UxUz_cov	$m^2 \cdot s^{-2}$	Covariance of U_x and U_z	Always
UyUz_cov	$m^2 \cdot s^{-2}$	Covariance of U_y and U_z	Always
TsUx_cov	deg $C \cdot m \cdot s^{-1}$	Covariance of T_s and U_x	Always
TsUy_cov	deg $C \cdot m \cdot s^{-1}$	Covariance of T_s and U_y	Always
TsUz_cov	deg $C \cdot m \cdot s^{-1}$	Covariance of T_s and U_z	Always
USTAR_R	$m \cdot s^{-1}$	Friction velocity after coordinate rotations	Always
U	$m \cdot s^{-1}$	Mean streamwise wind speed after coordinate rotations	Always
U_SIGMA	$m \cdot s^{-1}$	Standard deviation of streamwise wind after coordinate rotations	Always
V	$m \cdot s^{-1}$	Average crosswind speed after coordinate rotations	Always
V_SIGMA	$m \cdot s^{-1}$	Standard deviation of crosswind after coordinate rotations	Always
W	$m \cdot s^{-1}$	Average vertical wind speed after coordinate rotations	Always

TABLE C-22. Data Fields in the Flux_Notes Output Table

Data Field Name	Units	Description	Data Field Included
W_SIGMA	$m \cdot s^{-1}$	Standard deviation of vertical wind after coordinate rotations	Always
UV_cov	$m \cdot s^{-1}$	Covariance of streamwise and crosswind after coordinate rotations	Always
UW_cov	$m \cdot s^{-1}$	Covariance of streamwise and crosswind after coordinate rotations	Always
VW_cov	$m \cdot s^{-1}$	Covariance of crosswind and vertical wind after coordinate rotations	Always
UT_SONIC_Cov	$m \cdot °C \cdot s^{-1}$	Covariance of streamwise wind and sonic temperature after coordinate rotations	Always
VT_SONIC_Cov	$m \cdot °C \cdot s^{-1}$	Covariance of crosswind and sonic temperature after coordinate rotations	Always
WT_SONIC_Cov	$m \cdot °C \cdot s^{-1}$	Covariance of vertical wind (after coordinate rotations) and sonic temperature	Always
UW_Cov_fc	$m^2 \cdot s^{-2}$	Covariance of streamwise and vertical wind after coordinate rotations and frequency corrections	Always
VW_Cov_fc	$m^2 \cdot s^{-2}$	Covariance of cross and vertical wind after coordinate rotations and frequency corrections	Always
WT_SONIC_Cov_fc	$m \cdot °C \cdot s^{-1}$	Covariance of vertical wind and sonic temperature after coordinate rotations and frequency corrections	Always
WT_SONIC_Cov_fc_SND	$m \cdot °C \cdot s^{-1}$	Covariance of vertical wind and sonic temperature after coordinate rotations, frequency corrections, and SND correction	Always
sonic_samples	count	Number of raw sonic samples in averaging period without diagnostic flags	Always
no_sonic_head_Tot	count	Number of sonic samples where no sonic head was detected	Always
no_new_sonic_data_Tot	count	Number of scans where no sonic data were received	Always
sonic_amp_l_f_Tot	count	Number of sonic samples with amplitude low diagnostic flag	Always
sonic_amp_h_f_Tot	count	Number of sonic samples with amplitude high diagnostic flag	Always
sonic_sig_lck_f_Tot	count	Number of sonic samples with signal lock diagnostic flag	Always
sonic_del_T_f_Tot	count	Number of sonic samples with delta temp diagnostic flag	Always

TABLE C-22. Data Fields in the Flux_Notes Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
sonic_aq_sig_f_Tot	count	Number of sonic samples with acquiring signal diagnostic flag	Always
sonic_low_volt_f_Tot	count	Number of sonic samples with low voltage flag	Always
sonic_trig_f_Tot	count	Number of sonic samples with trigger flag	Always
sonic_intrnl_hmdty_f_Tot	count	Number of sonic samples with high internal humidity flag	Always
sonic_cal_err_f_Tot	count	Number of sonic samples with calibration error diagnostic flag	Always
UxH2O_Cov	$g \cdot m^{-2} \cdot s^{-1}$	Covariance of U_x and water vapour density (without O_2 correction)	Always
UyH2O_Cov	$g \cdot m^{-2} \cdot s^{-1}$	Covariance of U_y and water vapour density (without O_2 correction)	Always
UzH2O_Cov	$g \cdot m^{-2} \cdot s^{-1}$	Covariance of U_z and water vapour density (without O_2 correction)	Always
UH2O_Cov	$g \cdot m^{-2} \cdot s^{-1}$	Covariance of streamwise wind and H_2O density after coordinate rotations and covariance maximization (without O_2 correction)	Always
VH2O_Cov	$g \cdot m^{-2} \cdot s^{-1}$	Covariance of crosswind and H_2O density after coordinate rotations and covariance maximization (without O_2 correction)	Always
WH2O_Cov	$g \cdot m^{-2} \cdot s^{-1}$	Covariance of vertical wind and H_2O density after coordinate rotations, O_2 correction, and covariance maximization	Always
WH2O_Cov_fc	$g \cdot m^{-2} \cdot s^{-1}$	Covariance of vertical wind and H_2O density after coordinate rotations, oxygen correction, covariance maximization, and frequency corrections	Always
O2_crrctn_1	$g \cdot m^{-2} \cdot s^{-1}$	First KH20 oxygen correction	Always
O2_crrctn_2	$g \cdot m^{-2} \cdot s^{-1}$	Second KH20 oxygen correction	Always
H2O_E_WPL_fc	$g \cdot m^{-2} \cdot s^{-1}$	H_2O flux WPL correction term due to water vapour flux after coordinate rotations and frequency corrections	Always
H2O_T_WPL_fc	$g \cdot m^{-2} \cdot s^{-1}$	H_2O flux WPL correction term due to sensible heat flux after coordinate rotations and frequency corrections	Always
H2O_samples	count	Number of H_2O samples without diagnostic flags	Always

TABLE C-22. Data Fields in the Flux_Notes Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
UxFW_Cov	deg C·m·s^{-1}	Covariance of U_x and fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used
UyFW_Cov	deg C·m·s^{-1}	Covariance of U_y and fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used
UzFW_Cov	deg C·m·s^{-1}	Covariance of U_z and fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used
UFW_Cov	deg C·m·s^{-1}	Covariance of streamwise wind and fine-wire thermocouple temperature after coordinate rotations and covariance maximization	If FW05, FW1, or FW3 is used
VFW_Cov	deg C·m·s^{-1}	Covariance of crosswind and fine-wire thermocouple temperature after coordinate rotations and covariance maximization	If FW05, FW1, or FW3 is used
WFW_Cov	deg C·m·s^{-1}	Covariance of vertical wind and fine-wire thermocouple temperature after coordinate rotations and covariance maximization	If FW05, FW1, or FW3 is used
WFW_Cov_fc	deg C·m·s^{-1}	Covariance of vertical wind and fine-wire thermocouple temperature after coordinate rotations, covariance maximization, and frequency corrections	If FW05, FW1, or FW3 is used
FW_samples	count	The number of valid fine-wire thermocouple measurements in the averaging period from which covariances may be calculated	If FW05, FW1, or FW3 is used
alpha	decimal degrees	Alpha angle used for coordinate rotations (regardless of planar fit or double rotation method, angle convention of Wilczak et al. 2001 used)	Always
beta	decimal degrees	Beta angle used for coordinate rotations (regardless of planar fit or double rotation method, angle convention of Wilczak et al. 2001 used)	Always
gamma	decimal degrees	Gamma angle used for coordinate rotations (regardless of planar fit or double rotation method, angle convention of Wilczak et al. 2001 used)	Always
height_measurement	m	User entered measurement height of EC sensors	Always
height_canopy	m	User entered canopy height	Always
surface_type_text	text	User entered surface type	Always

TABLE C-22. Data Fields in the Flux_Notes Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
displacement_user	m	User entered displacement height; 0 for auto calculation	Always
d	m	Displacement height used in calculations; it will equal displacement_user if user entered a non-zero value; if displacement_user is zero, program will auto calculate	Always
roughness_user	m	Roughness length entered by user (if left as 0, the program autocalculates a value)	Always
z0	m	Roughness length; if roughness_user = 0, z0 is determined by the program; if roughness_user ≠ 0, z0 is set to roughness_user.	Always
z	m	Aerodynamic height	Always
MO_LENGTH	m	Monin-Obukhov length	Always
ZL	$m \cdot m^{-1}$	Atmospheric surface layer stability	Always
iteration_FreqFactor	count	Number of iterations for recalculating Monin-Obukhov length and frequency factors	Always
latitude	decimal degrees	Latitude; positive for Nothern hemisphere, negative for Southern hemisphere	Always
longitude	decimal degrees	Longitude; positive for Eastern hemisphere, negative for Western hemisphere	Always
altitude	m	Altitude of site above sea level	Always
UTC_OFFSET	h	Time offset in hours at site relative to universal time	Always
separation_x_kh20	m	Separation between sonic and KH20 with respect to sonic x-axis	Always
separation_y_kh20	m	Separation between sonic and KH20 with respect to sonic y-axis	Always
separation_lat_dist_kh20	m	Separation distance between sonic and KH20 along the axis perpendicular to oncoming wind	Always
separation_lag_dist_kh20	m	Separation distance between sonic and KH20 along the axis parallel to oncoming wind	Always
separation_lag_scan_kh20	scans	Number of scans to lag KH20 data relative to sonic data to account for separation along the axis of oncoming wind and wind velocity	Always

TABLE C-22. Data Fields in the Flux_Notes Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
separation_x_FW	m	Separation between sonic and fine-wire thermocouple with respect to sonic x-axis	If FW05, FW1, or FW3 is used
separation_y_FW	m	Separation between sonic and fine-wire thermocouple with respect to sonic y-axis	If FW05, FW1, or FW3 is used
FW_diameter	m	Effective diameter of fine-wire thermocouple junction	If FW05, FW1, or FW3 is used
separation_lat_dist_FW	m	Separation distance between sonic and fine-wire thermocouple along axis perpendicular to oncoming wind	If FW05, FW1, or FW3 is used
separation_lag_dist_FW	m	Separation distance between sonic and fine-wire thermocouple along axis parallel to oncoming wind	If FW05, FW1, or FW3 is used
separation_lag_scan_FW	scans	Number of scans to lag fine-wire thermocouple data relative to sonic data to account for separation along axis of oncoming wind and wind velocity	If FW05, FW1, or FW3 is used
time_const_FW	m	Calculated time constant of the fine-wire thermocouple	If FW05, FW1, or FW3 is used
MAX_LAG	scans	Maximum number of scans to lag KH20 or fine-wire thermocouple data with respect to sonic data when doing cross correlation for covariance maximization. For example, if MAX_LAG = 2, the program will consider lags of −2, −1, 0, +1, and +2.	Always
lag_kh20	scans	The lag applied to KH20 data with respect to sonic data that maximizes covariance	Always
lag_FW	scans	The lag applied to fine-wire thermocouple data with respect to sonic data that maximizes covariance	Always
FreqFactor_UW_VW	number	Frequency correction factor applied to momentum fluxes	Always
FreqFactor_WT_SONIC	number	Frequency correction factor applied to wTs covariance	Always
FreqFactor_WH2O	number	Frequency correction factor applied to wH_2O covariance values	Always
FreqFactor_WFW	number	Frequency correction factor applied to fine-wire thermocouple derived wFW covariance	Always

TABLE C-22. Data Fields in the Flux_Notes Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
rho_d_probe	$g \cdot m^{-3}$	Average density of dry air calculated from temp/RH probe data	Always
rho_a_probe	$kg \cdot m^{-3}$	Average density of ambient moist air calculated from temp/RH probe data	Always
Cp	$J \cdot kg^{-1} \cdot K^{-1}$	Specific heat of ambient (moist) air at constant pressure	Always
Lv	$J \cdot g^{-1}$	Latent heat of vapourization	Always
T_panel	deg C	Average temperature of the data-logger wiring panel	Always
batt_volt	volt	Average battery voltage supplying power to the data logger	Always
slowsequence_Tot	count	Number of slow sequences during the averaging interval (for example, the number of times biomet and energy balance sensors were measured)	Always
nr01_heater_secs	s	Number of seconds NR01 heater was powered in interval	If NR01 used
cnr4_fan_secs	s	Number of seconds CNR4 fan was powered in interval	If CNR4 used
cnr4_fan_freq_max	Hz	Maximum frequency of CNR4 fan in interval	If CNR4 used
cnr4_fan_freq_min	Hz	Minimum frequency of CNR4 fan in interval	If CNR4 used
cnr4_heater_1_secs	s	Number of seconds CNR4 heater #1 was powered in interval	If CNR4 used
cnr4_heater_2_secs	s	Number of seconds CNR4 heater #2 was powered in interval	If CNR4 used
sn500_heater_secs	s	Number of seconds SN500SS heater was powered in interval	If SN500SS used
V_CS320	mV	Average raw voltage output from CS320	If CS320 used
T_CS320	deg C	Average temperagure of CS320	If CS320 used
X_incline	decimal deg	Average incline with respect to sensor x-axis	If CS320 used
Y_incline	decimal deg	Average incline with respect to sensor y-axis	If CS320 used
Z_incline	decimal deg	Average incline with respect to sensor z-axis	If CS320 used
shfp_cal_x_1_1	$W \cdot m^{-2} \cdot mV^{-1}$	Calibration multiplier currently used for soil heat flux plates; x is an index indicating the number of sensors	If HFP01 or HFP01SC used

TABLE C-22. Data Fields in the Flux_Notes Output Table			
Data Field Name	**Units**	**Description**	**Data Field Included**
shfp_cal_fail_x_1_1	none	Result of TRUE indicates HFP01SC returned an invalid number or the calibrated sensitivity was not within 80%-105% of the original sensitivity	If HFP01SC used
process_time	ms	Average processing time for each scan	Always
process_time_Max	Ms	Maximum processing time for a scan	Always
buff_depth_Max	Number	Maximum number of records stored in the buffer	Always

C.4.5 Program Sequence of Measurement and Corrections

The following are the main correction procedures and algorithms implemented in the program. The oxygen correction is unique to the KH20; see Appendix D, *Equations and Algorithms of Water Vapour Density and Water Flux in KH20 Eddy-Covariance Systems* *(p. D-1)*. For the other corrections, more details about the theory and implementation may be found in the appendices of the *EasyFlux DL CR6OP* manual.

1. Despike and filter 10 Hz data using sonic and KH20 diagnostic codes.

2. Coordinate rotations with an option to use the double rotation method (Tanner and Thurtell 1969), or planar fit method (Wilczak et al. 2001).

3. Lag CO_2 and H_2O measurements against sonic wind measurements for maximization of CO_2 and H_2O fluxes (Horst and Lenschow 2009, Foken et al. 2012), with additional constraints to ensure lags are physically possible.

4. Apply oxygen correction to covariances with water density from the KH20. (See Appendix D, *Equations and Algorithms of Water Vapour Density and Water Flux in KH20 Eddy-Covariance Systems* *(p. D-1)*.)

5. Frequency corrections using commonly used cospectra (Moore 1986, van Dijk 2002a, Moncrieff et al. 1997) and transfer functions of block averaging (Kaimal et al. 1989), line/volume averaging (Moore 1986, Moncrieff et al. 1997, Foken et al. 2012, van Dijk 2002a), time constants (Montgomery 1947, Shapland et al. 2014, Geankoplis 1993), and sensor separation (Horst and Lenschow 2009, Foken et al. 2012).

6. A modified SND correction (Schotanus et al. 1983) to derive sensible heat flux from sonic sensible heat flux following the implementation as outlined in van Dijk 2002b. Additionally, fully corrected real sensible heat flux computed from fine-wire thermometry may be provided.

7. Correction for air density changes using WPL equations (Webb et al. 1980).

8. Data quality qualifications based on steady state conditions, surface-layer turbulence characteristics, and wind directions following Foken et al. 2012 (or Foken et al. 2004 for the Flux_AmeriFluxFormat output table).

9. If energy balance sensors are used, calculation of energy closure based on energy balance measurements and corrected sensible and latent heat fluxes.

10. Footprint characteristics are computed using Kljun et al (2004) and Kormann and Meixner (2001).

C.5 References

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Appendix D. Equations and Algorithms of Water Vapour Density and Water Flux in KH20 Eddy-Covariance Systems

D.1 Fundamental Equation

A krypton hygrometer (KH20, Campbell Scientific) is a fast-response water vapour analyzer to measure the high-frequency fluctuations of water vapour 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 vapour 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 vapour and oxygen. Given water vapour 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:

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

where, on wavelengths 1 and 2, k_{w1} and k_{w2} with subscript w indicating water are the absorption coefficients of water vapour and k_{o1} and k_{o2} with subscript o indicating oxygen are the absorption coefficients of oxygen. Water vapour has similar absorption at both wavelengths (Campbell Scientific Inc. 2010), thus

$k_{w1} \approx k_{w2}$ and absorption coefficients of water vapour 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:

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

This is the fundamental equation for KH20 measurements.

D.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 calibration process under the calibration 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 calibration process, given in KH20 Calibration; 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}).

D.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 vapour 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 vapouur mass mixing ratio (ratio of mean water vapour to mean dry air density computed in the data processing).

As usual in eddy-covariance measurements, the covariance variables:

$w^{'}\left(\ln V\right)^{'}$ 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 vapour density ($\ln V$) cannot be found in previous documents from Campbell Scientific.

D.4 Frequency Response of KH20

KH20 measures the water vapour density averaged over a cylindrical light path that has a diameter of 9.5 mm and length of 11 to 15 mm (see KH20 Calibration). 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)

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