



EASYFLUX DL CR6OP  
For CR6 and Open-Path  
Eddy-Covariance System

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# EasyFlux<sup>®</sup> DL CR6OP

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## 1. Introduction

*EasyFlux<sup>®</sup> DL CR6OP* is a CRBasic program that enables a CR6 data logger to collect fully corrected fluxes of CO<sub>2</sub>, latent heat (H<sub>2</sub>O), sensible heat, ground surface heat flux (optional), and momentum from a Campbell Scientific open-path eddy-covariance (EC) system with optional GPS and energy balance sensors. The program processes the EC data using commonly used corrections in the scientific literature. Because the number of analog channels on the CR6 is limited, the program also supports the addition of a CDM-A116 analog channel expansion module, which allows a full suite of energy balance sensors, thus enabling the program to calculate the ground surface heat flux and energy closure. Specifically, the program supports data collection and processing from the following sensors.

### **Gas analyzer and sonic anemometer (qty 1)**

Supports one combination of gas analyzer and sonic anemometer.

- EC150 with CSAT3A
- IRGASON

### **GPS Receiver (optional, qty 0 to 1)**

- GPS16X-HVS

### **Fine-wire thermocouple (optional, qty 0 to 1)**

- FW05
- FW1
- FW3

### **Bimeteorology (biomet) and energy balance sensors (optional)**

- Temperature/Relativity Humidity (RH) Probe (qty 0 to 1)
  - HC2S3
  - HMP155A
- Radiation measurements
  - Option 1
    - NR-LITE2 Net Radiometer (qty 0 to 1)
    - CS300 or LI200X Pyranometer (qty 0 to 1)
    - LI190SB Quantum Sensor (qty 0 to 1)
    - SI-111 Infrared Radiometer (qty 0 to 1)
  - Option 2
    - NR01 or CNR4 4-Way Radiometers (qty 0 to 1)
- TE525MM Rain Gage (qty 0 to 1)
- TCAV Soil Thermocouple Probe (qty 0 to 2)
- Soil Water Content Reflectometer (qty 0 to 2)
  - CS616
  - CS650
  - CS655
- Soil Heat Flux Plates
  - Option 1: HFP01 plates (qty 0 to 4)
  - Option 2: HFP01SC self-calibrating plates (qty 0 to 4)

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**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** In this manual, “IRGA” refers to either the EC150 or the IRGASON infrared gas analyzer, “sonic anemometer” refers to either the CSAT3A or IRGASON sonic anemometer, and “FW” refers to a FW05, FW1, or FW3 fine-wire thermocouple.

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## 2. Precautions

- *EasyFlux DL CR6OP* requires the CR6 to have operating system (OS) version 06.08 or newer, the EC100 to have OS version 07.05 or newer, and the CDM-A116 to have OS 02.10 or newer.
- The program applies the most common open-path 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 CR6OP* or another tool.
- As *EasyFlux DL CR6OP* 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.

## 3. Installation

### 3.1 Wiring

Install of sensors and system components according to the respective product manuals. When wiring the sensors to the data logger or CDM-A116, the default wiring schemes, along with the number of instruments *EasyFlux DL CR6OP* supports, should be followed if the standard version of the program is being used. TABLE 3-1 through TABLE 3-11 present the wiring schemes.

An IRGA with an associated sonic anemometer are the only required sensors for the program. The additional sensors described in the following tables are optional. Many of the optional sensors are wired to a CDM-A116 module, which effectively increases the CR6 analog channels since the CR6 itself does not contain enough channels for a full energy balance sensor suite. If one or more of the optional sensors are not used, the data logger or CDM module terminals assigned to those sensor wires should be left unwired.

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**NOTE** If the standard data-logger program is modified, the wiring presented in TABLE 3-1 may no longer apply. In these cases, refer directly to the program code to determine proper wiring.

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### 3.1.1 IRGA and Sonic Anemometer

An open-path IRGA and sonic anemometer must be connected to the EC100 electronics, and the EC100 must be wired to a CR6 data logger for *EasyFlux DL CR6OP* to be functional. TABLE 3-1 shows the default wiring for these sensors.

TABLE 3-1. Default Wiring for IRGA and Sonic Anemometer				
Sensor	Quantity	Wire Description	Color	CR6 Terminal
IRGASON or EC150/CSAT3A (from EC100)	1	SDM Data	Green	C1
		SDM Clock	White	C2
		SDM Enable	Red/Brown	C3
		Signal Ground	Black	G (power ground)
		Shield	Clear	AG $\perp$ (analog ground)

### 3.1.2 CDM-A116 Module

Due to the limitations on channel count of the CR6, a CDM-A116 module is required when using a fine-wire thermocouple, any of the radiation sensors except the NR-Lite2, or any of the soil sensors. If using a CDM-A116 prepare the instrument as follows:

1. Connect the module to a 10-32 VDC power source.
2. Launch Campbell Scientific's *Device Configuration Utility* software (v2.12 or newer) and select **CDM-A100 Series** among the list of **Peripheral** devices. If this is the first time connecting, follow the instruction on the main screen to download the USB driver to the computer.
3. Select the appropriate COM port and click on the **Connect** button.
4. Use a Cat5e or Cat6 Ethernet Cable (included with the CDM-A116) to connect the CPI port on the module to the CR6 CPI port.

### 3.1.3 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 3-2 shows the default wiring for the GPS16X-HVS.

TABLE 3-2. Default Wiring for GPS Receiver				
Sensor	Quantity	Wire Description	Color	CR6 Terminal
GPS16X-HVS	0 or 1	PPS	Grey	U1
		TXD	White	U2
		Shield	Clear	AG $\perp$
		12V	Red	12V
		Power Ground	Black	G

### 3.1.4 Fine-Wire Thermocouple

Several models of fine-wire thermocouple sensors are available that can be integrated with the IRGA and sonic anemometer for direct measurements of sensible heat flux. The *EasyFlux DL CR6OP* can support from zero to one fine-wire thermocouple along with the IRGA and sonic anemometer. Shown in TABLE 3-3 are the available types and default wiring for adding a fine-wire thermocouple.

TABLE 3-3. Default Wiring for Fine-Wire Thermocouple				
Sensor	Quantity	Wire Description	Color	CDM-A116 Terminal
FW05, FW1, or FW3	0 or 1	Signal	Purple	CDM Diff 3H
		Signal Reference	Red	CDM Diff 3L
		Shield	Clear	CDM AG $\perp$

### 3.1.5 Temperature and Relative Humidity Probe

The *EasyFlux DL CR6OP* can support from zero to one temperature and relative humidity probe with the IRGA and sonic anemometer. The default wiring for the HC2S3/HMP155A is shown in TABLE 3-4.

#### NOTE

There are two options for a temperature and relative humidity probe, the HC2S3 and the HMP155A. For details and specifications of these probes, visit [www.campbellsci.com](http://www.campbellsci.com). The physical wiring to the CR6 data logger is the same for each sensor. The colors of the wires, however, are different. The wire colors for the HMP155A sensor are noted by italic text in TABLE 3-4.

TABLE 3-4. Default Wiring for Temperature and Relative Humidity Probe				
Sensor	Quantity	Wire Description	Color	CR6 Terminal
HC2S3/ HMP155A	0 or 1	Temp Signal	Brown/ <i>Yellow</i>	U7
		Temp Signal Reference	Yellow/ <i>White</i>	U8 <sup>1/</sup>
		RH Signal	White/ <i>Blue</i>	U9
		RH Signal Reference	Yellow/ <i>White</i>	U10 <sup>1/</sup>
		Shield	Clear/ <i>Clear</i>	AG $\perp$
		Power	Green/ <i>Red</i>	+12 V
		Power Ground	Grey/ <i>Black</i>	G
<sup>1/</sup> A jumper wire should be added to connect U8 to U10.				

### 3.1.6 Radiation Measurements Option 1

There are two options for making radiation measurements with *EasyFlux DL CR6OP*. The program can support any combination of the four sensors described in TABLE 3-5. Alternatively, it can support one of the two types of four-way radiometers described in TABLE 3-6. TABLE 3-5 gives the default wiring for Option 1. TABLE 3-6 shows the details of the default wiring for Option 2.

TABLE 3-5. Default Wiring for Radiation Measurement Option 1				
Sensor	Quantity	Wire Description	Color	Terminal
NR-LITE2 Net Radiometer	0 or 1	Radiation Signal	Red	CR6 U11
		Signal Reference	Blue <sup>1/</sup>	CR6 U12
		Shield	Black	CR6 AG ⚬
CS300 or LI200X Pyranometer	0 or 1	Signal	Red	CDM Diff 9H
		Signal Reference	Black	CDM Diff 9L <sup>2/</sup>
		Signal Ground	White (no white for CS300)	CDM AG ⚬
		Shield	Clear	CDM AG ⚬
LI190SB Quantum Sensor	0 or 1	Signal	Red	CDM Diff 10H
		Signal Reference	Black	CDM Diff 10L <sup>1/</sup>
		Shield	Clear	CDM AG ⚬
SI-111 Infrared Radiometer	0 or 1	Target Temp Signal	Red	CDM Diff 11H
		Target Temp Reference	Black	CDM Diff 11L
		Shield	Clear	CDM AG ⚬
		Sensor Temp Signal	Green	CDM Diff 12H
		Sensor Temp Reference	Blue	CDM AG ⚬
		Voltage Excitation	White	CDM X4

<sup>1/</sup>Jumper to ⚬ with user-supplied wire  
<sup>2/</sup>Unlike the LI200X, the CS300 requires a jumper wire to connect CDM Diff 9L to CDM AG (analog ground)

### 3.1.7 Radiation Measurements Option 2

Two models of four-way radiometers are compatible with the program *EasyFlux DL CR6OP*. However, only one model at a time can be used due to channel limitations. The default wiring for each of the four-way radiometers is shown in TABLE 3-6.

TABLE 3-6. Default Wiring for Radiation Measurements Option 2				
Sensor	Quantity	Wire Description	Color	CDM-A116 Terminal
NR01 4-Way Radiometer	0 or 1	Pyranometer Up Signal	Red (cbl 1)	CDM Diff 9H
		Pyranometer Up Reference	Blue <sup>1/</sup> (cbl 1)	CDM Diff 9L <sup>1/</sup>
		Pyranometer Down Signal	White (cbl 1)	CDM Diff 10H
		Pyranometer Down Reference	Green <sup>1/</sup> (cbl 1)	CDM Diff 10L <sup>1/</sup>
		Pyrgeometer Up Signal	Brown (cbl 1)	CDM Diff 11H
		Pyrgeometer Up Reference	Yellow <sup>1/</sup> (cbl 1)	CDM Diff 11L <sup>1/</sup>
		Pyrgeometer Down Signal	Purple (cbl 1)	CDM Diff 12H
		Pyrgeometer Down Reference	Grey <sup>1/</sup> (cbl 1)	CDM Diff 12L <sup>1/</sup>
		PT100 Signal	White (cbl 2)	CDM Diff 4H
		PT100 Reference	Green (cbl 2)	CDM Diff 4L
		Current Excite	Red (cbl 2)	CDM X3
		Current Return	Blue (cbl 2)	CDM AG $\perp$
		Shields	Clear	CDM AG $\perp$
CNR4 4-Way Radiometer	0 or 1	Pyranometer Up Signal	Red	CDM Diff 9H
		Pyranometer Up Reference	Blue <sup>1/</sup>	CDM Diff 9L <sup>1/</sup>
		Pyranometer Down Signal	White	CDM Diff 10H
		Pyranometer Down Reference	Black <sup>1/</sup>	CDM Diff 10L <sup>1/</sup>
		Pyrgeometer Up Signal	Grey	CDM Diff 11H
		Pyrgeometer Up Reference	Yellow <sup>1/</sup>	CDM Diff 11L <sup>1/</sup>
		Pyrgeometer Down Signal	Brown	CDM Diff 12H
		Pyrgeometer Down Reference	Green <sup>1/</sup>	CDM Diff 12L <sup>1/</sup>
		Thermistor Signal	White	CDM Diff 4H
		Thermistor V Excite	Red	CDM X3
		Thermistor Reference	Black	CDM AG $\perp$
		Shields	Clear	CDM AG $\perp$

<sup>1/</sup>Jumper to  $\perp$  with user-supplied wire

### 3.1.8 Precipitation Gage

*EasyFlux DL CR6OP* can support a single TE525MM tipping rain gage, or a precipitation gage can be omitted. The default wiring for the precipitation gage is shown in TABLE 3-7.

TABLE 3-7. Default Wiring for Precipitation Gage				
Sensor	Quantity	Wire Description	Color	CR6 Terminal
TE525MM Tipping Rain Gage	0 or 1	Pulse Output	Black	U6
		Signal Ground	White	AG $\perp$
		Shield	Clear	AG $\perp$

### 3.1.9 Soil Temperature

The TCAV is an averaging soil thermocouple probe used for measuring soil temperature. *EasyFlux DL CR6OP* can support up to two 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 3-8. An additional TCAV sensor would be wired according to TCAV #2 in TABLE 3-8.

#### CAUTION

If only one TCAV is being used and it is wired to terminals 2H and 2L (leaving terminals 1H and 1L empty), the data logger will not record any TCAV measurements.

TABLE 3-8. Default Wiring for Soil Thermocouple Probes				
Sensor	Quantity	Wire Description	Color	CDM-A116 Terminal
TCAV #1	1	Signal	Purple	CDM Diff 1H
		Signal Reference	Red	CDM Diff 1L
		Shield	Clear	CDM AG $\perp$
TCAV #2	1	Signal	Purple	CDM Diff 2H
		Signal Reference	Red	CDM Diff 2L
		Shield	Clear	CDM AG $\perp$

#### 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 CR6OP* 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 3-9.

### 3.1.10 Soil Water Content

*EasyFlux DL CR6OP* supports one of three models of soil water content sensors: CS616, CS650, or CS655; up to two 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 3-9.

#### CAUTION

If only one soil water content sensor is being used, wire it according to the first probe as described in TABLE 3-9. If only one sensor is being used and it is wired according to the second sensor, *EasyFlux DL CR6OP* will not record any measurements from the soil water content sensor.

**TABLE 3-9. Default Wiring for Soil Water Content Probes**

Sensor	Quantity	Wire Description	Color	CR6 Terminal
CS616 #1	1	Power	Red	+12 V
		Signal Output	Green	U3
		Enable	Orange	U5
		Signal Ground	Black	AG $\perp$
		Power Ground	Clear	G
CS616 #2	1	Power	Red	+12 V
		Signal Output	Green	U4
		Enable	Orange	U5
		Signal Ground	Black	AG $\perp$
		Power Ground	Clear	G
CS650/CS655 #1	1	SDI-12 Data	Green	U3
		SDI-12 Power	Red	+12 V
		SDI-12 Reference	Black	G
		Shield	Clear	G
		Not Used	Orange	AG $\perp$
CS650/CS655 #2	1	SDI-12 Data	Green	U3
		SDI-12 Power	Red	+12 V
		SDI-12 Reference	Black	G
		Shield	Clear	AG $\perp$
		Not Used	Orange	G



### 3.1.11 Soil Heat Flux Plates

*EasyFlux DL CR6OP* can support from zero to four standard (non-self-calibrating) soil heat flux plates. The default wiring for the standard soil heat flux plates is shown in TABLE 3-10.

TABLE 3-10. Default Wiring for Non-Calibrating Soil Heat Flux Plates				
Sensor	Quantity	Wire Description	Color	CDM-A116 Terminal
HFP01 #1	1	Signal	White	CDM Diff 5H
		Signal Reference	Green	CDM Diff 5L
		Shield	Clear	CDM AG $\perp$
HFP01 #2	1	Signal	White	CDM Diff 6H
		Signal Reference	Green	CDM Diff 6L
		Shield	Clear	CDM AG $\perp$
HFP01 #3	1	Signal	White	CDM Diff 7H
		Signal Reference	Green	CDM Diff 7L
		Shield	Clear	CDM AG $\perp$
HFP01 #4	1	Signal	White	CDM Diff 8H
		Signal Reference	Green	CDM Diff 8L
		Shield	Clear	CDM AG $\perp$

### 3.1.12 Self-Calibrating Soil Heat Flux Plates

*EasyFlux DL CR6OP* can also support from zero to four of the self-calibrating soil heat flux plates described in TABLE 3-11. The default wiring for the self-calibrating soil heat flux plates is shown in TABLE 3-11.

TABLE 3-11. Default Wiring for Soil Heat Flux Plates (Self Calibrating)				
Sensor	Quantity	Wire Description	Color	CDM-A116 Terminal
HFP01SC #1	1	Signal	White	CDM Diff 5H
		Signal Reference	Green	CDM Diff 5L
		Shield	Clear	CDM AG $\perp$
		Heater Signal	Yellow	CDM Diff 13H
		Heater Reference	Purple	CDM Diff 13L
		Shield	Clear	CDM AG $\perp$
		Heater Power	Red	CDM SW12-1 <sup>1/</sup>
		Power Reference	Black	CDM G
HFP01SC #2	1	Signal	White	CDM Diff 6H
		Signal Reference	Green	CDM Diff 6L
		Shield	Clear	CDM AG $\perp$
		Heater Signal	Yellow	CDM Diff 14H
		Heater Reference	Purple	CDM Diff 14L

**TABLE 3-11. Default Wiring for Soil Heat Flux Plates (Self Calibrating)**

Sensor	Quantity	Wire Description	Color	CDM-A116 Terminal
		Shield	Clear	CDM AG $\perp$
		Heater Power	Red	CDM SW12-1 <sup>1/</sup>
		Power Reference	Black	CDM G
HFP01SC #3	1	Signal	White	CDM Diff 7H
		Signal Reference	Green	CDM Diff 7L
		Shield	Clear	CDM AG $\perp$
		Heater Signal	Yellow	CDM Diff 15H
		Heater Reference	Purple	CDM Diff 15L
		Shield	Clear	CDM AG $\perp$
		Heater Power	Red	CDM SW12-2 <sup>1/</sup>
		Power Reference	Black	CDM G
HFP01SC #4	1	Signal	White	CDM Diff 8H
		Signal Reference	Green	CDM Diff 8L
		Shield	Clear	CDM AG $\perp$
		Heater Signal	Yellow	CDM Diff 16H
		Heater Reference	Purple	CDM Diff 16L
		Shield	Clear	CDM AG $\perp$
		Heater Power	Red	CDM SW12-2 <sup>1/</sup>
		Power Reference	Black	CDM G

<sup>1/</sup>The SW12 ports on the CDM-A116 are limited to 200mA output. Accordingly, no more than two HFP01SC sensors may be connected to each port. Connect heater power wires from HFP01SC #1 and #2 to SW12-1, and connect heater wires from HFP01SC #3 and #4 to SW12-2.

## 4. Operation

### 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 *CRBasic Editor* or CR1000KD Keyboard Display (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad or LoggerNet* (p. 12), for use of CR1000KD Keyboard Display).

Open the program in *CRBasic Editor* or another text editor. After the introductory comments at the top is a section titled “USER-DEFINED CONFIGURATION CONSTANTS” (see FIGURE 4-1). 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 can be maintained.

One program function constant that should be mentioned specifically is the **ONE\_FULL\_TABLE** constant. 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 Section 4.4, *Output Tables* (p. 22).

### 2. Sensor Selection Constants

All sensor selection constants begin with the prefix *SENSOR*. The value is set to **-1** as **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 **-1** as **TRUE**. When set to **TRUE**, the wiring in TABLE 3-11 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 **0** as **FALSE**.

### 3. Sensor Quantity Constants

The value for these constants indicates the number of each type of sensor in the system. For example, if four soil heat flux (SHF) plates were being used, the constant **NMBR\_SHF** would be set to **4**.

### 4. Sensor Calibration Constants

Some sensors have unique parameters for their measurement working equations (e.g., 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's 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, all of the constants dealing with the Temp/RH probe are grouped together with the **SENSOR\_TMPR\_RH** constant at the top. If a Temp/RH probe is not being used, **SENSOR\_TMPR\_RH** should be set to **FALSE** and the next four constants dealing with multipliers and offsets will be conditionally excluded in the program.

---

After all constants are verified, the program should be saved. 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* user-interface software.

```

20 '*****
21 '*** USER-DEFINED CONFIGURATION CONSTANTS ***
22 '*****
23
24 'Start of Constants Customization Section
25 ConstTable (Const_Table)
26
27 '*PROGRAM FUNCTION CONSTANTS
28 Const SCAN_INTERVAL = 100 'Unique: measurement rate (ms): 40 ms (25 Hz), 50 ms (20 Hz), 100 ms (10 Hz), 200 ms (5
29 Const SLOWSEQUENCE_SCAN_INTERVAL = 5000 'Unique: slow sequence measurement rate (ms) >3000 ms and <6000ms (Note: SDI-12 sensors
30 Const OUTPUT_INTERVAL = 30 'Unique: online flux data output interval (minutes).
31 Const NMBR_DAY_FLUX_CRD = 30 'Unique: number of days of Flux_AmeriFluxFormat, Flux_CSIFormat, Flux_Notes table data b
32 Const NMBR_DAY_TIMESERIES_CRD = 1 'Unique: number of days of Time_Series table data to store in each file on the card. Num
33 Const FIRST_NOTCH_FREQ_SLOW_SEQU = 60 'Unique: slowsequence analog measurement integration time, 60 for 60Hz (e.g. in US, Cana
34 Const ONE_FULL_TABLE = 0 'Unique: -1 if all half-hourly or hourly data in Flux_CSIFormat and Flux_Notes are store
35
36 '*PERIPHERAL
37 Const PERIPHERAL_CDM_A116 = -1 'Unique: A CDM-A116 is being used with the CR6 (required for full suite of energy balance
38 Const CDM_SN As Long = 1001 'Unique: CDM-A116 serial number
39 Const CPI_ADDR_CDM As Long = 2 'Unique: CPI address for CDM-A116
40 Const CPI_DEVICE_DSCRPTN = "EasyFlux_CDM_A116" 'Unique: CDM Module name or identifier
41
42 '* GAS ANALYZER AND SONIC ANEMOMETER
43 Const SENSOR_IRGASON = -1 'Unique: IRGASON, if TRUE, SENSOR_CSAT3AEC150 must be set to FALSE
44 Const SENSOR_CSAT3AEC150 = 0 'Unique: CSAT3A + EC150, if TRUE, SENSOR_IRGASON must be set to FALSE.
45 Const SDM_PER = 30 'Unique: default SDM clock speed (uS). May need to increase if using long cables and ski
46 Const EC100_SDM_ADDR As Long = 1 'Unique: SDM address for EC100.
47 Const BANDWIDTH = 20 'Unique: in Hz. For spectral analysis, set to 1/2 sampling freq. Options: 5, 10, 12.5, 2
48
49 '*GPS
50 Const SENSOR_GPS16X = 0 'Unique: GPS16X-HVS GPS receiver with integrated antenna
51 Const UTC_OFFSET = -6 'Unique: The local time, in hours, from UTC/GMT. The time in Logan, UT, US is 6 hour beh
52
53 '*FINE WIRE THERMOCOUPLE
54 Const SENSOR_FW = -1 'Unique: FW05, FW1, FW3, or other fine wire thermocouple
55
56 '*TEMP/RH PROBE
57 Const SENSOR_TMPR_RH = -1 'Unique: HC2S3 or HMP155A: temperature and relative humidity probe
58 #If (SENSOR_TMPR_RH) Then
59 Const TMPR_T_MULT As Float = 0.14 'Unique: multiplier for temperature; HC2S3 = 0.1, HMP155A = 0.14, or HMP45C = 0.1.
60 Const TMPR_T_OFFSET As Float = -80.0 'Unique: offset for temperature; HC2S3 = -40, HMP155A = -80, or HMP45C = -40.
61 Const TMPR_RH_MULT As Float = 0.1 'Unique: multiplier for RH: HC2S3 = 0.1, HMP155A = 0.1, or HMP45C = 0.1.
62 Const TMPR_RH_OFFSET As Float = 0.0 'Unique: offset for RH: HC2S3 = 0, HMP155A = 0, or HMP45C = 0.
63 #EndIf
64

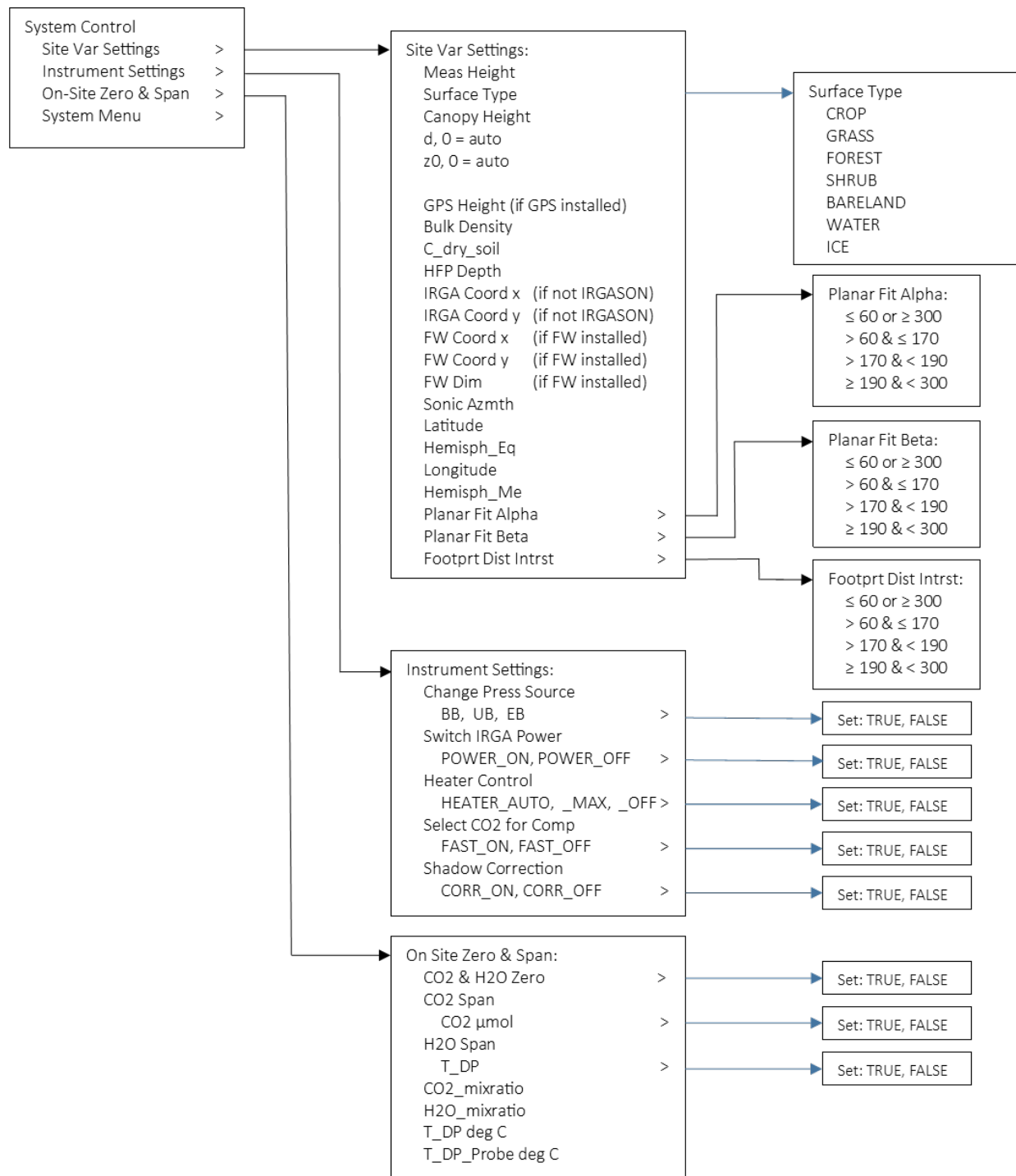
```

FIGURE 4-1. Example screen from CRBasic Editor showing user-defined configuration constants

## 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 4-2). 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 4-2 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 LoggerNet connect screen's numeric display of variables from the Public table.



**FIGURE 4-2.** 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 4-1 gives short descriptions of each station variable.

TABLE 4-1. Station Variables with Descriptions

Station Variable	Units	Default	Description	Name of variable in Public Table (in case no CR1000KD available)
Meas Height	m	2	The height of the center of the eddy-covariance sensor measurement volumes above ground.	height_measurement
Surf Type	adimensional	GRASS	Type of surface at the measurement site. Options are CROP, GRASS, FOREST, SHRUB, BARELAND, and WATER. This is used to estimate displacement height (see Appendix D.6.1, <i>Aerodynamic Height</i> (p. D-8)) and roughness length (see Appendix G.1.3, <i>Programmatic Approach</i> (p. G-7)).	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 Appendix D.6.1, <i>Aerodynamic Height</i> (p. D-8), for details.	displacement_user
z <sub>0</sub>	m	0 (Auto)	Roughness length. Set to zero (0) for program to auto-calculate. See Appendix G.1.3, <i>Programmatic Approach</i> (p. G-7), for details.	roughness_user
GPS Height	m	1	The height of the GPS reciever above the ground surface. If GPS is not used, this variable is omitted.	height_GPS16X
Bulk Density	kg·m <sup>-3</sup>	1300	Average bulk density of soil. If energy balance sensors are not used, this variable is omitted.	soil_bulk_density
C_dry_soil	J·kg <sup>-1</sup> K <sup>-1</sup>	870	Specific heat of dry mineral soil. If energy balance sensors are not used, this variable is omitted.	cds
HFP Depth	m	0.08	Depth of the soil heat flux plates. If energy balance sensors are not used, this variable is omitted.	thick_abv_HFP

TABLE 4-1. Station Variables with Descriptions

Station Variable	Units	Default	Description	Name of variable in Public Table (in case no CR1000KD available)
IRGA Coord x	m	0 for IRGASON; 0.04066 for EC150	Distance along the sonic x-axis between the sonic sampling volume and the gas analyzer sampling volume. If an IRGASON is used, this should be set to 0. If an EC150 with CSAT3A is used, this defaults to 0.04066, which corresponds to the EC150 mounting position closest to the CSAT3A sonic measurement volume.	separation_x_IRGA
IRGA Coord y	m	0 for IRGASON; 0.02905 for EC150	Distance along the sonic y-axis between the sonic sampling volume and the gas analyzer sampling volume. If an IRGASON is used, this should be set to 0. If an EC150 with CSAT3A is used, this defaults to 0.02905, which corresponds to the EC150 mounting position closest to the CSAT3A sonic measurement volume.	separation_y_IRGA
FW Coord x	m	0.005870	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	0.03259	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	FW05_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 $1.27 \times 10^{-5}$ , $2.54 \times 10^{-5}$ , and $7.62 \times 10^{-5}$ m, respectively. If no fine-wire thermocouple is being used, this variable is omitted.	FW_diameter
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

**TABLE 4-1. Station Variables with Descriptions**

TABLE 4-1. 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		adimensional	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		adimensional	WEST	The site longitudinal hemisphere. Options are EAST or WEST.	hemisphere_EW 1 = East -1 = West
Altitude		m	1356	The site altitude	altitude
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). <sup>1/</sup>	alpha_PF_60_300
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). <sup>1/</sup>	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). <sup>1/</sup>	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). <sup>1/</sup>	alpha_PF_190_300



TABLE 4-1. Station Variables with Descriptions

Station Variable		Units	Default	Description	Name of variable in Public Table (in case no CR1000KD available)
Planar Fit Beta	$\leq 60$ or $\geq 300$	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). <sup>1/</sup>	beta_PF_60_300
Planar Fit Beta	$> 60$ & $\leq 170$	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). <sup>1/</sup>	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). <sup>1/</sup>	beta_PF_170_190
Planar Fit Beta	$\geq 190$ & $< 300$	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). <sup>1/</sup>	beta_PF_190_300
Footprint Dist of Interest	$\leq 60$ or $\geq 300$	m	100z	<p>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).</p> <p>Note: The program will report the percentage of cumulative footprint from within this distance. The default value is 100 times the aerodynamic height, <math>z</math>. Recall that <math>z</math> is the difference between the measurement height and displacement height.</p>	dist_intrst_60_300

**TABLE 4-1. Station Variables with Descriptions**

Station Variable		Units	Default	Description	Name of variable in Public Table (in case no CR1000KD available)
Footprint Dist of Interest	> 60 & ≤ 170	m	100z	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	100z	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_intrst_170_190
Footprint Dist of Interest	≥ 190 & < 300	m	100z	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

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

TABLE 4-2. Instrument Settings with Descriptions

Station Variable		Default	Description	Name of variable in Public Table (in case no CR1000KD available)
Change Pressure Source	Select Source	EB	Used to select the barometer to use for measurements of ambient pressure. Set to <b>EB</b> for EC100 enhanced barometer. Set to <b>BB</b> for the EC100 on-board basic barometer.	press_source 0 = Basic Barometer 1 = Added by user 2 = Enhanced Barometer (EB)
	Set Source	FALSE	If the variable <b>Select Source</b> has been changed, this variable must be set to <b>TRUE</b> to enable the change. The program will return <b>Set Source</b> to <b>FALSE</b> once the change has been applied.	set_press_source_flg -1 = True 0 = False
Switch IRGA Power	IRGA Power	POWER_ON	Used to power down or power on the gas analyzer head. The EC100 electronics and sonic anemometer will continue to be powered. Options are <b>POWER_ON</b> or <b>POWER_OFF</b> .	IRGA_power 0 = Power On 1 = Power Off
	Set IRGA Power	FALSE	If the variable <b>Select IRGA Power</b> has been changed, this variable must be set to <b>TRUE</b> to enable the change. The program will return <b>Set IRGA Power</b> to <b>FALSE</b> once the change has been applied.	set_IRGA_power_flg -1 = True 0 = False
Heater Control	Enable Heater Control	HEATER_AUTO	Used to enable the automatic window heater control by selecting <b>HEATER_AUTO</b> or to disable the window heaters by selecting <b>HEATER_OFF</b> .	heater -1 = off -2 = auto
	Set Heater Control	FALSE	If the variable <b>Enable Heater Control</b> has been changed, this variable must be set to <b>TRUE</b> to enable the change. The program will return <b>Set Heater Control</b> to <b>FALSE</b> once the change has been applied.	set_heater_flg -1 = True 0 = False

TABLE 4-2. Instrument Settings with Descriptions

Station Variable		Default	Description	Name of variable in Public Table (in case no CR1000KD available)
Spectroscopic correction	Enable the use of CO <sub>2</sub> from fast air temperature	FAST_ON	Used to enable the use of CO <sub>2</sub> corrected for spectroscopic effect from air temperature measured by fast response sensors. The use is controlled by selecting <b>FAST_ON</b> or to disable this use by selecting <b>FAST_OFF</b> .	select_CO2_fast_tmpr TRUE = FAST_ON FALSE = FAST_OFF
	Set Use option for CO <sub>2</sub>	FALSE	If the variable <b>CO2 fast T</b> has been changed, this variable must be set to <b>TRUE</b> to enable the change. The program will return <b>Set CO2 Selected</b> to <b>FALSE</b> once the change has been applied.	set_CO2_fast_tmpr_flg -1 = True 0 = False
Shadow Correction	Enable Shadow Correction	CORR_OFF	Used to enable the Kaimal sonic transducer wind shadowing correction as described in the CSAT3B manual. <b>CORR_ON</b> enables the correction, while <b>CORR_OFF</b> disables it.	shadow_corr -1 = CORR_ON 0 = CORR_OFF
	Set Shadow Correction	FALSE	If the variable <b>Enable Shadow Correction</b> has been changed, this variable must be set to <b>TRUE</b> to enable the change. The program will return <b>Set Shadow Correction</b> to <b>FALSE</b> once the change has been applied.	set_shadow_corr_flg -1 = True 0 = False

TABLE 4-3. On-Site Zero and Span Variables

TABLE 4-3. On-Site Zero and Span Variables					
On-Site Zero & Span Variable		Units	Default	Description	Name of variable in Public Table (in case no CR1000KD available)
Set Zero		adimensional	FALSE	Set this to <b>TRUE</b> after flowing zero gas through the zero/span shroud and reaching equilibrium.	set_zero_flg -1 = True 0 = False
Span Concentrations	CO <sub>2</sub>	ppm	0	This is the concentration of span gas flowing through the zero/span shroud. It should be on a basis of dry air.	CO2_span_gas
	T_DP	°C	0	This is the dewpoint temperature of the H <sub>2</sub> O span gas generated from a dewpoint generator. It should match the dewpoint temperature setting on the generator.	T_DP_span_gas
Set CO <sub>2</sub> Span		adimensional	FALSE	Set this to <b>TRUE</b> after flowing CO <sub>2</sub> span gas through the zero/span shroud and reaching equilibrium.	set_CO2_span_flg -1 = True 0 = False
Set H <sub>2</sub> O Span		adimensional	FALSE	Set this to <b>TRUE</b> after flowing H <sub>2</sub> O span gas through the zero/span shroud and reaching equilibrium.	set_H2O_span_flg -1 = True 0 = False
CO <sub>2</sub> _mixratio		ppm	–	This is a real-time measurement of CO <sub>2</sub> molar mixing ratio (dry basis) as measured by the gas analyzer. This can be monitored to know when equilibrium has been reached.	CO2_mixratio
H <sub>2</sub> O_mixratio		ppth	–	This is a real-time measurement of H <sub>2</sub> O molar mixing ratio (dry basis) as measured by the gas analyzer. This can be monitored to know when equilibrium has been reached.	H2O_mixratio
Td		deg C	–	This is a real-time measurement of dewpoint temperature as measured by the gas analyzer.	T_DP
Td_probe		deg C	–	This is a real-time measurement of dewpoint temperature derived from measurements by the temp/RH probe. It is omitted if there is no temp/RH probe being used. This value could potentially be input for dewpoint temperature, Td above, if a dewpoint generator is unavailable and performing a rough H <sub>2</sub> O span is helpful (for example, during troubleshooting).	T_DP_Probe

### 4.3 Data Retrieval

The program stores a very limited amount of data to the internal CPU of the data logger, so a microSD Flash card should be used with the CR6. TABLE 4-4 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 4-4. microSD Flash Card Fill Times**

microSD Flash card size	Fill time with gas analyzer and sonic only	Fill time with gas analyzer, sonic, FW, and biomet/energy balance sensors) <sup>1/</sup>
2 GB	~29 days	~23 days
8 GB	~121 days	~92 days
16 GB	~242 days	~184 days
<sup>1/</sup> Biomet and energy balance sensors used for this fill time estimate include the following: HMP155A, NR-LITE2, CS300, LI200X, LI190SB, SI-111, TE525MM, TCAV (qty 2), CS616 (qty 2), and HFP01 (qty 4)		

#### 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 4-4 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.

### 4.4 Output Tables

Besides the standard **Public**, **Status**, and **TableInfo** tables that every data logger reports, the program has six output tables. TABLE 4-5 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 the *EasyFlux DL CR6OP*. Additionally, an output table called **Flux\_AmeriFluxFormat** reports the variables in the order and format prescribed by AmeriFlux (see <http://ameriflux.lbl.gov/data/aboutdata/data-variables/>).

The **Flux\_CSFormat** and **Flux\_Notes** tables have the same content as they did in prior versions of *EasyFlux DL* for CR3000 (v1.0), although variable names

have been updated to conform to AmeriFlux convention. 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 Section 4.1, *Set Constants in CRBasic Editor and Load Program* (p. 10), on changing constants).

TABLE 4-5. Data Output Tables

Table Name	Description	Recording Interval	Memory on CR3000 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)	Time_Series is broken up into 1 day files (see TABLE 4-4)
Diagnostic	Reports most recent diagnostic flags from gas analyzer and sonic anemometer	SCAN_INTERVAL (default 100 ms)	1 record (most recent scan)	0 records
EC100_Config	Reports settings for the gas analyzer and sonic anemometer	When settings are changed or system is power cycled	Whenever EC100 is reconfigured	Until card is full (see TABLE 4-4)
Flux_AmeriFluxFormat	Processed flux and statistical data following reporting conventions and order of AmeriFlux	OUTPUT_INTERVAL (default 30 minutes)	NUM_DAY_CPU (default 7 days)	Broken up into 30-day files; see TABLE 4-4 for number of files
Flux_CSFormat	Processed flux and statistical data	OUTPUT_INTERVAL (default 30 minutes)	NUM_DAY_CPU (default 7 days)	Broken up into 30-day files; see TABLE 4-4 for number of 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)	Broken up into 30-day files; see TABLE 4-4 for number of files

TABLE 4-5 through TABLE 4-11 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 4-6. Data Fields in the Time\_Series Data Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
Ux	$\text{m}\cdot\text{s}^{-1}$	Wind speed along sonic x-axis	Always
Uy	$\text{m}\cdot\text{s}^{-1}$	Wind speed along sonic y-axis	Always
Uz	$\text{m}\cdot\text{s}^{-1}$	Wind speed along sonic z-axis	Always
T_SONIC	deg C	Sonic temperature	Always
diag_sonic	adimensional	Raw sonic diagnostic value (0 indicates no diagnostic flags set)	Always
CO2_density	$\text{mg}\cdot\text{m}^{-3}$	CO <sub>2</sub> density	Always
CO2_density_fast_tmpr	$\text{mg}\cdot\text{m}^{-3}$	CO <sub>2</sub> density whose spectroscopy correction using fast response temperature	Always
H2O_density	$\text{g}\cdot\text{m}^{-3}$	Water vapor density	Always
diag_irga	adimensional	Raw gas analyzer diagnostic value (0 indicates no diagnostic flags set)	Always
T_SONIC_corr	deg C	Air temperature derived from sonic temperature corrected for humidity and pressure	If IRGASON is used
TA_1_1_1	deg C	Air temperature measured by the EC100 temperature probe	Always
PA	kPa	Ambient pressure	Always
CO2_sig_strgth	adimensional	CO <sub>2</sub> signal strength	Always
H2O_sig_strgth	adimensional	H <sub>2</sub> O signal strength	Always
FW	deg C	Air temperature measured by fine-wire thermocouple	If FW05, FW1, or FW3 is used



**TABLE 4-7. Data Fields in the Diagnostic Output Table**

<b>Data Field Name</b>	<b>Description</b>	<b>Data Field Included</b>
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_cal_err_f	Calibration error diagnostic flag	Always
irga_bad_data_f	Any gas analyzer diagnostic flag is set	Always
irga_gen_fault_f	General system fault diagnostic flag	Always
irga_startup_f	Startup diagnostic flag	Always
irga_motor_spd_f	Motor speed diagnostic flag	Always
irga_tec_tmpr_f	Thermoelectric cooler (TEC) temperature diagnostic flag	Always
irga_src_pwr_f	Source power diagnostic flag	Always
irga_src_tmpr_f	Source temperature diagnostic flag	Always
irga_src_curr_f	Source current diagnostic flag	Always
irga_off_f	Gas head power down diagnostic flag	Always
irga_sync_f	Synchronization diagnostic flag	Always
irga_amb_tmpr_f	Ambient temperature probe diagnostic flag	Always
irga_amb_press_f	Ambient pressure diagnostic flag	Always
irga_CO2_I_f	CO <sub>2</sub> I signal diagnostic flag	Always
irga_CO2_Io_f	CO <sub>2</sub> Io signal diagnostic flag	Always
irga_H2O_I_f	H <sub>2</sub> O I signal diagnostic flag	Always
irga_H2O_Io_f	H <sub>2</sub> O Io signal diagnostic flag	Always
irga_CO2_Io_var_f	CO <sub>2</sub> Io variation diagnostic flag	Always
irga_H2O_Io_var_f	H <sub>2</sub> O Io variation diagnostic flag	Always
irga_CO2_sig_strgth_f	CO <sub>2</sub> signal strength diagnostic flag	Always
irga_H2O_sig_strgth_f	H <sub>2</sub> O signal strength diagnostic flag	Always
irga_cal_err_f	Calibration file read error flag	Always
irga_htr_ctrl_off_f	Heater control off diagnostic flag	Always

**TABLE 4-8. Data Field in the Config\_Setting\_Notes Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
bandwidth_freq	Hz	EC100 bandwidth (5, 10, 12, or 20 for 5 Hz, 10 Hz, 12.5 Hz, or 20 Hz respectively)	Always
press_source	adimensional	Sensor used by EC100 for ambient pressure (0 for EC100 Basic Barometer, 1 for user/custom barometer, 2 for EC100 Enhanced Barometer)	Always
tmpr_source	adimensional	Sensor used by EC100 for ambient temperature (0 for EC100 Temperature Probe, no other values valid)	Always
CO2_zero_coeff	adimensional	CO <sub>2</sub> zero coefficient set from last CO <sub>2</sub> zero	Always
CO2_span_coeff	adimensional	CO <sub>2</sub> span coefficient set from last CO <sub>2</sub> span	Always
H2O_zero_coeff	adimensional	H <sub>2</sub> O zero coefficient set from last H <sub>2</sub> O zero	Always
H2O_span_coeff	adimensional	H <sub>2</sub> O span coefficient set from last H <sub>2</sub> O span	Always
CO2_span_mixra	ppm	CO <sub>2</sub> mixing ratio of span gas	Always
H2O_span_T_DP	deg C	Dew point temperature of span gas	Always
Heater_control	adimensional	Heater Control Setting (-1 for disabled, -2 for auto control)	Always
IRGA_power	adimensional	Gas head power state (0 for on, 1 for off)	Always
CO2_fast_tmpr	adimensional	If <b>TRUE</b> , CO <sub>2</sub> with spectroscopy correction using fast air temperature is used for flux calculation. If <b>FALSE</b> , conventional CO <sub>2</sub> is used.	Always
Shadow_corr	adimensional	Application of transducer shadowing correction (0 for off, 1 for on)	Always

**TABLE 4-9. Data Fields in the Flux\_AmeriFluxFormat Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
TIMESTAMP_START	YYYYMMDDHHMM	Start time of the averaging period	Always
TIMESTAMP_END	YYYYMMDDHHMM	End time of the averaging period	Always
CO2	$\mu\text{mol}\cdot\text{mol}^{-1}$	CO <sub>2</sub> mole fraction	Always
CO2_SIGMA	$\mu\text{mol}\cdot\text{mol}^{-1}$	Standard deviation of CO <sub>2</sub>	Always
H2O	$\text{mmol}\cdot\text{mol}^{-1}$	Average H <sub>2</sub> O molar mixing ratio (dry basis)	Always
H2O_SIGMA	$\text{mmol}\cdot\text{mol}^{-1}$	Standard deviation of H <sub>2</sub> O	Always
FC	$\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$	CO <sub>2</sub> flux after corrections	Always
FC_SSITC_TEST	adimensional	Result of steady state and integral turbulence characteristics for FC according to Foken et al. (2004)	Always
LE	$\text{W}\cdot\text{m}^{-2}$	Latent heat flux after corrections	Always

**TABLE 4-9. Data Fields in the Flux\_AmeriFluxFormat Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
LE_SSITC_TEST	adimensional	Result of steady state and integral turbulence characteristics for LE according to Foken et al. (2004)	Always
ET	mm·hour <sup>-1</sup>	Evapotranspiration	Always
ET_SSITC_TEST	adimensional	Result of steady state and integral turbulence characteristics for ET according to Foken et al. (2004)	Always
H	W·m <sup>-2</sup>	Sensible heat flux after corrections	Always
H_SSITC_TEST	adimensional	Result of steady state and integral turbulence characteristics for FC according to Foken et al. (2004)	Always
G	W·m <sup>-2</sup>	Calculated heat flux at the ground surface	If energy balance sensors used
SG	W·m <sup>-2</sup>	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 Appendix G, <i>Footprint (p. G-1)</i> , 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·s <sup>-1</sup>	Average wind speed	Always
WS_MAX	m·s <sup>-1</sup>	Maximum wind speed	Always
USTAR	m·s <sup>-1</sup>	Friction velocity	Always
ZL	adimensional	Stability	Always
TAU	kg·m <sup>-1</sup> ·s <sup>-2</sup>	Momentum Flux	Always
TAU_SSITC_TEST	adimensional	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·s <sup>-1</sup>	Average streamwise wind	Always

**TABLE 4-9. Data Fields in the Flux\_AmeriFluxFormat Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
U_SIGMA	m·s <sup>-1</sup>	Standard deviation of streamwise wind	Always
V	m·s <sup>-1</sup>	Average crosswind	Always
V_SIGMA	m·s <sup>-1</sup>	Standard deviation of crosswind	Always
W	m·s <sup>-1</sup>	Average vertical wind	Always
W_SIGMA	m·s <sup>-1</sup>	Standard deviation of vertical wind	Always
PA	kPa	Atmospheric Pressure	Always
TA_1_1_1	°C	Air temperature from EC100 temperature probe	Always
RH_1_1_1	%	Relative humidity calculated from EC100 temperature probe, H2O (from analyzer), and pressure.	Always
T_DP_1_1_1	deg C	Dewpoint temperature calculated from EC100 temperature probe, H2O (from analyzer), and pressure.	Always
TA_2_1_1	deg C	Air temperature calculated from sonic temperature, H2O, and pressure.	Always
RH_2_1_1	%	Relative humidity calculated from sonic temperature, H2O, and pressure.	Always
T_DP_2_1_1	deg C	Dewpoint temperature calculated from sonic temperature, H2O, and pressure.	Always
TA_3_1_1	deg C	Air temperature from temp/RH probe	If temp/RH probe used
RH_3_1_1	%	Relative humidity from temp/RH probe	If temp/RH probe used
T_DP_3_1_1	deg C	Dewpoint temperature from temp/RH probe	If temp/RH probe used
VPD	hPa	Vapor pressure deficit	If temp/RH probe used
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 CS616 or CS65X used

**TABLE 4-9. Data Fields in the Flux\_AmeriFluxFormat Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
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	adimensional	Albedo	If NR01 or CNR4 is used
NETRAD	$W \cdot m^{-2}$	Net radiation	If NR01, CNR4 or NRI12 is used
PPFD_IN	$\mu mol \cdot m^{-2} \cdot s^{-1}$	Photosynthetic photon density	If LI190SB is used
SW_IN	$W \cdot m^{-2}$	Incoming shortwave radiation	If NR01, CNR4, LI200X, or CS300 used
SW_OUT	$W \cdot m^{-2}$	Outgoing shortwave radiation	If NR01, CNR4, LI200X, or CS300 used
LW_IN	$W \cdot m^{-2}$	Incoming longwave radiation	If NR01 or CNR4 used
LW_OUT	$W \cdot m^{-2}$	Outgoing longwave radiation	If NR01 or CNR4 used
P	mm	Precipitation in output interval	If TE525 used
T_CANOPY	deg C	Canopy temperature	If SI111 used

**TABLE 4-10. Data Fields in the Flux\_CSFormat Data Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
FC_mass	$mg \cdot m^{-2} \cdot s^{-1}$	Final corrected CO <sub>2</sub> flux	Always
FC_QC	grade	Overall quality grade for Fc_molar and Fc_mass following Foken et al. 2012	Always
FC_samples	count	The total number of time series samples used in calculation of Fc	Always
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

**TABLE 4-10. Data Fields in the Flux\_CSFormat Data Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
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, NR01, or CNR4 is 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 over surface heat flux plus net radiation	If energy balance sensors are used
poor_energy_closure_flg	adimensional	If <b>TRUE</b> , energy closure is poor due to unknown reasons	If energy balance sensors are 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
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 EC100 temperature probe	Always
RH_1_1_1	deg C	Relative humidity calculated from TA_1_1_1 (EC100 temperature probe), water vapor density, and pressure.	Always
T_DP_1_1_1	deg C	Average dewpoint temperature calculated using temperature from the EC100 temperature probe	Always

**TABLE 4-10. Data Fields in the Flux\_CSFormat Data Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
amb_e	kPa	Average water vapor pressure calculated using temperature from the EC100 temperature probe	Always
amb_e_sat	kPa	Average saturated water vapor pressure calculated using temperature from the EC100 temperature probe	Always
TA_2_1_1	deg C	Average ambient temperature calculated from sonic temperature, water vapor density, and pressure	Always
RH_2_1_1	deg C	Average dewpoint temperature calculated using sonic temperature, water vapor density, and pressure	Always
T_DP_2_1_1	deg C	Average dewpoint temperature calculated using sonic temperature, water vapor density, and pressure	Always
e	kPa	Average water vapor pressure calculated from sonic temperature	Always
e_sat	kPa	Average saturated water vapor pressure calculated from sonic temperature	Always
TA_3_1_1	deg C	Average air temperature from temp/RH probe	If temp/RH probe used
RH_3_1_1	%	Average relative humidity from temp/RH probe	If temp/RH probe used
T_DP_3_1_1	deg C	Average dewpoint temperature from temp/RH probe	If temp/RH probe used
e_probe	kPa	Average saturation vapor pressure derived from gas analyzer measurements	If temp/RH probe used
e_sat_probe	kPa	Average vapor pressure derived from gas analyzer measurements	If temp/RH probe used
H2O_probe		Average water vapor density derived from temp/RH probe measurements	If temp/RH probe used
PA	kPa	Average ambient air pressure	Always
VPD	kPa	Vapor pressure deficit	Always
U <sub>x</sub>	m·s <sup>-1</sup>	Average U <sub>x</sub>	Always
U <sub>x</sub> _SIGMA	m·s <sup>-1</sup>	Standard deviation of U <sub>x</sub>	Always
U <sub>y</sub>	m·s <sup>-1</sup>	Average U <sub>y</sub>	Always
U <sub>y</sub> _SIGMA	m·s <sup>-1</sup>	Standard deviation of U <sub>y</sub>	Always
U <sub>z</sub>	m·s <sup>-1</sup>	Average U <sub>z</sub>	Always
U <sub>z</sub> _SIGMA	m·s <sup>-1</sup>	Standard deviation of U <sub>z</sub>	Always
T_SONIC	deg C	Average sonic temperature	Always

TABLE 4-10. Data Fields in the Flux\_CSFormat Data Output Table

Data Field Name	Units	Description	Data Field Included
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	$\text{m}\cdot\text{s}^{-1}$	Average wind speed	Always
WS_RSLT	$\text{m}\cdot\text{s}^{-1}$	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	$\text{m}\cdot\text{s}^{-1}$	Maximum wind speed	Always
CO2_density	$\text{mg}\cdot\text{m}^{-3}$	Average CO <sub>2</sub> mass density	Always
CO2_density_SIGMA	$\text{mg}\cdot\text{m}^{-3}$	Standard deviation of CO <sub>2</sub> mass density	Always
H2O_density	$\text{mmol}\cdot\text{mol}^{-1}$	Water vapor mass density	Always
H2O_density_SIGMA	$\text{mmol}\cdot\text{mol}^{-1}$	Standard deviation of water vapor mass density	Always
CO2_sig_strgth_Min	adimensional	Minimum CO <sub>2</sub> signal strength	Always
H2O_sig_strgth_Min	adimensional	Minimum H <sub>2</sub> O signal strength	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	$\text{W}\cdot\text{m}^{-2}$	Average net radiation (raw, not corrected for wind)	If NR-LITE2 is used
ALB	adimensional	Average albedo	If CNR4 or NR01 is used
SW_IN	$\text{W}\cdot\text{m}^{-2}$	Average incoming short wave radiation	If CNR4 or NR01 is used
SW_OUT	$\text{W}\cdot\text{m}^{-2}$	Average outgoing short wave radiation	If CNR4 or NR01 is used
LW_IN	$\text{W}\cdot\text{m}^{-2}$	Average incoming long wave radiation	If CNR4 or NR01 is used



**TABLE 4-10. Data Fields in the Flux\_CSFormat Data Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
LW_OUT	$W \cdot m^{-2}$	Average outgoing long wave radiation	If CNR4 or NR01 is used
T_nr	K	Average sensor body temperature	If CNR4 or NR01 is used
LW_in_meas	$W \cdot m^{-2}$	Average raw incoming long wave radiation	If CNR4 or NR01 is used
LW_out_meas	$W \cdot m^{-2}$	Average raw outgoing long wave radiation	If CNR4 or NR01 is used
PPFD_IN	$\mu mol \cdot s^{-1} \cdot m^{-2}$	Average density of photosynthetic active radiation	If LI190SB is used
sun_azimuth	decimal degrees	Solar azimuth	Always
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	adimensional	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 TCAV sensor; x is an index for the number of TCAV sensors	If TCAV is used
SWC_x_1_1	$m^3 \cdot m^{-3}$	Average volumetric soil water content for each CS616, CS650, or CS655; x is an index for the number of each sensor model above	If CS616, CS650, or CS655 sensors are used
CS616_wcr_x_1_1	$\mu s$	Average water content reflectometer period for each CS616; x is an index for the number of CS616 sensors	If CS616 is 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 is used
shf_plate_x_1_1	$W \cdot m^{-2}$	Average soil heat flux; x is an index for the number of HFP01 or HFP01SC	If HFP01 or HFP01SC is used

TABLE 4-10. Data Fields in the Flux\_CSFormat Data Output Table

Data Field Name	Units	Description	Data Field Included
shf_plate_x_1_1	$\text{W m}^{-2} \text{ mV}^{-1}$	Coefficients found from the HFP01SC self-calibration and used to calculate shf_plate_x_1_1; x is an index for the number of HFP01 or HFP01SC	If HFP01SC is 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
FETCH_55	m	Upwind distance that contains 55% of footprint	Always
FETCH_40	m	Upwind distance that contains 40% of footprint. If <b>NAN</b> is returned, integration of the model never reached 90% within the allowable distance of integration. See Appendix <a href="#">G</a> , <i>Footprint (p. G-1)</i> , 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 <b>Kljun</b> or <b>KormannMeixner</b> ; the model of Kljun et al. (2004) is used for applicable atmospheric conditions, else the model of Kormann & Meixner (2001) is used	Always

**TABLE 4-11. Data fields in the Flux\_Notes Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
UxUy_cov	$\text{m}^2 \cdot \text{s}^{-2}$	Covariance of $U_x$ and $U_y$	Always
UxUz_cov	$\text{m}^2 \cdot \text{s}^{-2}$	Covariance of $U_x$ and $U_z$	Always
UyUz_cov	$\text{m}^2 \cdot \text{s}^{-2}$	Covariance of $U_y$ and $U_z$	Always
TsUx_cov	$\text{deg C} \cdot \text{m} \cdot \text{s}^{-1}$	Covariance of $T_s$ and $U_x$	Always
TsUy_cov	$\text{deg C} \cdot \text{m} \cdot \text{s}^{-1}$	Covariance of $T_s$ and $U_y$	Always
TsUz_cov	$\text{deg C} \cdot \text{m} \cdot \text{s}^{-1}$	Covariance of $T_s$ and $U_z$	Always
USTAR_R	$\text{m} \cdot \text{s}^{-1}$	Friction velocity after coordinate rotations	Always
U	$\text{m} \cdot \text{s}^{-1}$	Mean streamwise wind speed after coordinate rotations	Always
U_SIGMA	$\text{m} \cdot \text{s}^{-1}$	Standard deviation of streamwise wind after coordinate rotations	Always
V	$\text{m} \cdot \text{s}^{-1}$	Average crosswind speed after coordinate rotations	Always
V_SIGMA	$\text{m} \cdot \text{s}^{-1}$	Standard deviation of crosswind after coordinate rotations	Always
W	$\text{m} \cdot \text{s}^{-1}$	Average vertical wind speed after coordinate rotations	Always
W_SIGMA	$\text{m} \cdot \text{s}^{-1}$	Standard deviation of vertical wind after coordinate rotations	Always
UV_cov	$\text{m} \cdot \text{s}^{-1}$	Covariance of streamwise and crosswind after coordinate rotations	Always
UW_cov	$\text{m} \cdot \text{s}^{-1}$	Covariance of streamwise and crosswind after coordinate rotations	Always
VW_cov	$\text{m} \cdot \text{s}^{-1}$	Covariance of crosswind and vertical wind after coordinate rotations	Always
UT_SONIC_Cov	$\text{m} \cdot ^\circ\text{C} \cdot \text{s}^{-1}$	Covariance of streamwise wind and sonic temperature after coordinate rotations	Always
VT_SONIC_Cov	$\text{m} \cdot ^\circ\text{C} \cdot \text{s}^{-1}$	Covariance of crosswind and sonic temperature after coordinate rotations	Always
WT_SONIC_Cov	$\text{m} \cdot ^\circ\text{C} \cdot \text{s}^{-1}$	Covariance of vertical wind (after coordinate rotations) and sonic temperature	Always
UW_Cov_fc	$\text{m}^2 \cdot \text{s}^{-2}$	Covariance of streamwise and vertical wind after coordinate rotations and frequency corrections	Always
VW_Cov_fc	$\text{m}^2 \cdot \text{s}^{-2}$	Covariance of cross and vertical wind after coordinate rotations and frequency corrections	Always
WT_SONIC_Cov_fc	$\text{m} \cdot ^\circ\text{C} \cdot \text{s}^{-1}$	Covariance of vertical wind and sonic temperature after coordinate rotations and frequency corrections	Always

TABLE 4-11. Data fields in the Flux\_Notes Output Table

Data Field Name	Units	Description	Data Field Included
WT_SONIC_Cov_fc_SND	$\text{m} \cdot ^\circ\text{C} \cdot \text{s}^{-1}$	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
sonic_aq_sig_f_Tot	count	Number of sonic samples with acquiring signal diagnostic flag	Always
sonic_cal_err_f_Tot	count	Number of sonic samples with calibration error diagnostic flag	Always
UxCO2_Cov	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of $U_x$ and $\text{CO}_2$ density	Always
UyCO2_Cov	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of $U_y$ and $\text{CO}_2$ density	Always
UzCO2_Cov	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of $U_z$ and $\text{CO}_2$ density	Always
UxH2O_Cov	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of $U_x$ and water vapor density	Always
UyH2O_Cov	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of $U_y$ and water vapor density	Always
UzH2O_Cov	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of $U_z$ and water vapor density	Always
UCO2_Cov	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of streamwise wind and $\text{CO}_2$ density after coordinate rotations	Always
VCO2_Cov	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of crosswind and $\text{CO}_2$ density after coordinate rotations	Always
WCO2_Cov	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of vertical wind and $\text{CO}_2$ density after coordinate rotations	Always
UH2O_Cov	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of streamwise wind and $\text{H}_2\text{O}$ density after coordinate rotations	Always
VH2O_Cov	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of crosswind and $\text{H}_2\text{O}$ density after coordinate rotations	Always

TABLE 4-11. Data fields in the Flux\_Notes Output Table

Data Field Name	Units	Description	Data Field Included
WH2O_Cov	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of vertical wind and H <sub>2</sub> O density after coordinate rotations	Always
WCO2_Cov_fc	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of vertical wind and CO <sub>2</sub> density after coordinate rotations and frequency corrections	Always
WH2O_Cov_fc	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	Covariance of vertical wind and H <sub>2</sub> O density after coordinate rotations and frequency corrections	Always
CO2_E_WPL_fc	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	CO <sub>2</sub> flux WPL correction term due to water vapor flux after coordinate rotations and frequency corrections	Always
CO2_T_WPL_fc	$\text{mg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	CO <sub>2</sub> flux WPL correction term due to sensible heat flux after coordinate rotations and frequency corrections	Always
H2O_E_WPL_fc	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	H <sub>2</sub> O flux WPL correction term due to water vapor flux after coordinate rotations and frequency corrections	Always
H2O_T_WPL_fc	$\text{g} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$	H <sub>2</sub> O flux WPL correction term due to sensible heat flux after coordinate rotations and frequency corrections	Always
CO2_samples	count	Number of CO <sub>2</sub> samples without diagnostic flags and within thresholds for CO <sub>2</sub> signal strength (set in code to default of 0.6, see Section 4.1, <i>Set Constants in CRBasic Editor and Load Program (p. 10)</i> ) and the factory calibrated CO <sub>2</sub> measurement range (0 to 1000 $\mu\text{mol/mol}$ )	Always
H2O_samples	count	Number of H <sub>2</sub> O samples without diagnostic flags and within thresholds for H <sub>2</sub> O signal strength (set in code to default of 0.7, see Section 4.1, <i>Set Constants in CRBasic Editor and Load Program (p. 10)</i> ) and the factory calibrated H <sub>2</sub> O measurement range (0 to 72 $\text{mmol/mol}$ )	Always
no_irga_head_Tot	count	Number of samples where no gas analyzer head was detected	Always
no_new_irga_data_Tot	count	Number of scans where no gas analyzer data were received	Always
irga_bad_data_f_Tot	count	Number of IRGA samples with any IRGA diagnostic flag set high	Always
irga_gen_fault_f_Tot	count	Number of gas analyzer samples with general system fault diagnostic flag	Always
irga_startup_f_Tot	count	Number of gas analyzer samples with startup diagnostic flag	Always

TABLE 4-11. Data fields in the Flux\_Notes Output Table

Data Field Name	Units	Description	Data Field Included
irga_motor_spd_f_Tot	count	Number of gas analyzer samples with motor speed diagnostic flag	Always
irga_tec_tmpr_f_Tot	count	Number of gas analyzer samples with TEC temperature diagnostic flag	Always
irga_src_pwr_f_Tot	count	Number of gas analyzer samples with source power diagnostic flag	Always
irga_src_tmpr_f_Tot	count	Number of gas analyzer samples with source temperature diagnostic flag	Always
irga_src_curr_f_Tot	count	Number of gas analyzer samples with source current diagnostic flag	Always
irga_off_f_Tot	count	Number of gas analyzer samples with gas head power down diagnostic flag	Always
irga_sync_f_Tot	count	Number of gas analyzer samples with synchronization diagnostic flag	Always
irga_amb_tmpr_f_Tot	count	Number of gas analyzer samples with ambient temperature probe diagnostic flag	Always
irga_amb_press_f_Tot	count	Number of gas analyzer samples with ambient pressure diagnostic flag	Always
irga_CO2_I_f_Tot	count	Number of gas analyzer samples with CO <sub>2</sub> I signal diagnostic flag	Always
irga_CO2_Io_f_Tot	count	Number of gas analyzer samples with CO <sub>2</sub> I <sub>o</sub> signal diagnostic flag	Always
irga_H2O_I_f_Tot	count	Number of gas analyzer samples with H <sub>2</sub> O I signal diagnostic flag	Always
irga_H2O_Io_f_Tot	count	Number of gas analyzer samples with H <sub>2</sub> O I <sub>o</sub> signal diagnostic flag	Always
irga_CO2_Io_var_f_Tot	count	Number of gas analyzer samples with CO <sub>2</sub> I <sub>o</sub> variation diagnostic flag	Always
irga_H2O_Io_var_f_Tot	count	Number of gas analyzer samples with H <sub>2</sub> O I <sub>o</sub> variation diagnostic flag	Always
irga_CO2_sig_strgth_f_Tot	count	Number of gas analyzer samples with CO <sub>2</sub> signal strength diagnostic flag	Always
irga_H2O_sig_strgth_f_Tot	count	Number of gas analyzer samples with H <sub>2</sub> O signal strength diagnostic flag	Always
irga_cal_err_f_Tot	count	Number of gas analyzer samples with calibration file read error flag	Always
irga_htr_ctrl_off_f_Tot	count	Number of gas analyzer samples with heater control off diagnostic flag	Always
UxFW_cov	deg C·m·s <sup>-1</sup>	Covariance of U <sub>x</sub> and fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used

**TABLE 4-11. Data fields in the Flux\_Notes Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
UyFW_cov	deg C·m·s <sup>-1</sup>	Covariance of U <sub>y</sub> and fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used
UzFW_cov	deg C·m·s <sup>-1</sup>	Covariance of U <sub>z</sub> and fine-wire thermocouple temperature	If FW05, FW1, or FW3 is used
UFW_cov	deg C·m·s <sup>-1</sup>	Covariance of streamwise wind and fine-wire thermocouple temperature after coordinate rotations	If FW05, FW1, or FW3 is used
VFW_cov	deg C·m·s <sup>-1</sup>	Covariance of crosswind and fine-wire thermocouple temperature after coordinate rotations	If FW05, FW1, or FW3 is used
WFW_cov	deg C·m·s <sup>-1</sup>	Covariance of vertical wind and fine-wire thermocouple temperature after coordinate rotations	If FW05, FW1, or FW3 is used
WFW_cov_fc	deg C·m·s <sup>-1</sup>	Covariance of vertical wind and fine-wire thermocouple temperature after coordinate rotations 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
displacement_user	m	User entered displacement height; 0 for auto calculation	Always

**TABLE 4-11. Data fields in the Flux\_Notes Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
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
z0	m	Roughness length	Always
z	m	Aerodynamic height	Always
MO_LENGTH	m	Monin-Obukhov length	Always
ZL	m·m <sup>-1</sup>	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 Northern hemisphere, negative for Southern hemisphere	Always
longitude	decimal degrees	Longitude; positive for Eastern hemisphere, negative for Western hemisphere	Always
separation_x_irga	m	Separation between sonic and gas analyzer with respect to sonic x-axis	Always
separation_y_irga	m	Separation between sonic and gas analyzer with respect to sonic y-axis	Always
separation_lat_dist_irga	m	Separation distance between sonic and gas analyzer along the axis perpendicular to oncoming wind	Always
separation_lag_dist_irga	m	Separation distance between sonic and gas analyzer along the axis parallel to oncoming wind	Always
separation_lag_scan_irga	scans	Number of scans to lag gas analyzer data relative to sonic data to account for separation along the axis of oncoming wind and wind velocity	Always
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



**TABLE 4-11. Data fields in the Flux\_Notes Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
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 gas analyzer 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_irga	scans	The lag applied to gas analyzer 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_WCO2_WH2O	number	Frequency correction factor applied to wCO <sub>2</sub> and wH <sub>2</sub> O covariance values	Always
FreqFactor_WFW	number	Frequency correction factor applied to fine-wire thermocouple derived wFW covariance	Always
amb_rho_d	g·m <sup>-3</sup>	Average density of dry air using air temperature from 107 probe	Always
amb_rho_a	kg·m <sup>-3</sup>	Average density of ambient moist air using air temperature from 107 probe	Always
rho_d	g·m <sup>-3</sup>	Average density of dry air using air temperature from sonic temperature	Always
rho_a	kg·m <sup>-3</sup>	Average density of ambient moist air using air temperature from sonic temperature	Always
rho_d_probe	g·m <sup>-3</sup>	Average density of dry air using air temperature from a HMP probe	HMP temperature and humidity probe is used

**TABLE 4-11. Data fields in the Flux\_Notes Output Table**

<b>Data Field Name</b>	<b>Units</b>	<b>Description</b>	<b>Data Field Included</b>
rho_a_probe	kg·m <sup>-3</sup>	Average density of ambient moist air using air temperature from a HMP probe	HMP temperature and humidity probe is used
Cp	J·kg <sup>-1</sup> ·K <sup>-1</sup>	Specific heat of ambient (moist) air at constant pressure	Always
Lv	J·g <sup>-1</sup>	Latent heat of vaporization	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
process_time_Avg	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

## 4.5 Program Sequence of Measurement and Corrections

The main correction procedures and algorithms implemented into the program are listed below. For more information on the sequence of measurements and corrections, refer to Appendix I, *EasyFlux DL CR6OP Process Flow Diagram (p. I-1)*. The appendices of this manual will give additional information on each major correction and its implementation in the program.

1. Despiking and filter 10 Hz data using sonic and gas analyzer diagnostic codes, and signal strength and measurement output range thresholds.
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<sub>2</sub> and H<sub>2</sub>O measurements against sonic wind measurements for maximization of CO<sub>2</sub> and H<sub>2</sub>O fluxes (Horst and Lenschow 2009, Foken et al. 2012), with additional constraints to ensure lags are physically possible.
4. 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).

5. 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.
6. Correction for air density changes using WPL equations (Webb et al. 1980).
7. 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).
8. If energy balance sensors are used, calculation of energy closure based on energy balance measurements and corrected sensible and latent heat fluxes.
9. Footprint characteristics are computed using Kljun et al (2004) and Kormann and Meixner (2001).

## 5. References

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# Appendix A. Vapor Pressure and Dewpoint Temperature

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IRGAs require an occasional span (i.e., field calibration) of water vapor. When doing a span, the humidity of the span gas must be known and entered using the On Site Zero & Span menu on the data-logger keypad (or alternatively, it is entered into *ECMon*, the IRGA user-interface software). Although this humidity may be expressed in various units, dewpoint temperature is used since the H<sub>2</sub>O span gas is typically generated with a dewpoint generator. Because dewpoint temperature is used, it is sometimes desirable to convert the water vapor density measurements of the IRGA to dewpoint temperature, especially as it provides comparability with the span gas before and after the span. Accordingly, the program converts water vapor density to dewpoint temperature using the algorithms described in this appendix.

## A.1 Equations to Calculate Dewpoint Temperature from Water Vapor Density

An EC system measures and reports water vapor density ( $\rho_w$  in g·m<sup>-3</sup>), air temperature ( $T$  in °C), and total atmospheric pressure ( $P$  in kPa). Using the ideal gas equation, vapor pressure ( $e$  in kPa) can be calculated using:

$$e = \rho_w R_v (T + 273.15) \quad (\text{A-1})$$

where:

$R_v$  is the gas constant for water vapor (4.61495·10<sup>-4</sup> kPa·m<sup>3</sup>·K<sup>-1</sup>·g<sup>-1</sup>)

In this equation, if  $e$  were saturation water vapor pressure ( $e_s$  in kPa),  $T$  would be dewpoint temperature ( $T_d$ ). However, since the air is unlikely to be saturated, other equations are needed to estimate the dewpoint temperature.

Buck (1981) developed equations to relate saturation water vapor pressure to dewpoint temperature in moist air. The equations were designed to be easily implemented in a computer program for conversion of saturation water vapor pressure to dewpoint temperature, or vice versa. The general model of equations was:

$$e_s = f_w(T_d, P) e_{ws}(T_d) \quad (\text{A-2})$$

where:

$e_s$  is saturation vapor pressure, and  $e_{ws}(T_d)$  is saturation vapor pressure of pure water at pressure of the sea level, given by:

$$e_{ws} = a \exp\left(\frac{bT_d}{T_d + c}\right) \quad (\text{A-3})$$

where:  $a$ ,  $b$ , and  $c$  are parameters, and  $f_w(T_d, P)$  is the enhancement factor that is the ratio of vapor pressure of moist air to that of pure water vapor, given by

$$f_w(T_d, P) = \frac{e_s}{e_{ws}} = A + P[B + C(T_d + D + EP)^2] \quad (\text{A-4})$$

where:

$A$ ,  $B$ ,  $C$ ,  $D$ , and  $E$  are parameters. In Buck (1981), Figure 1 and Table 2 show results for  $e_{ws}(T_d)$  from model (3), and Figure 3 and Table 3 show results for  $f_w(T_d, P)$  from model (4). Combining the saturation water vapor pressure equation, which has an error of  $\pm 0.05\%$  in a temperature range of  $-40$  to  $+50$  °C and within a normal range of surface layer pressures, with the enhancement factor, which has an equivalent error of  $\pm 0.05\%$  in the same temperature range, generates the following water vapor pressure equation for moist air:

$$e_s(T_d, P) = \begin{cases} 0.61121 \exp\left(\frac{17.368T_d}{T_d + 238.88}\right) f_w(T_d, P) & T_d \geq 0 \\ 0.61121 \exp\left(\frac{17.966T_d}{T_d + 247.15}\right) f_w(T_d, P) & T_d < 0 \end{cases} \quad (\text{A-5})$$

where:

$$f_w(T_d, P) = 1.00041 + P[3.48 \times 10^{-5} + 7.4 \times 10^{-9}(T_d + 30.6 - 0.38P)^2] \quad (\text{A-6})$$

Given measured water vapor pressure and total pressure from an EC system, the only unknown variable in equations (A-5) and (A-6) is dewpoint temperature. However, analytically solving the equations for  $T_d$  is not feasible due to complication from the quadratic term in equation (A-6). Fortunately, the enhancement factor is a very weak function of  $T_d$ , which is why Buck (1981) recommended that “a rough approximation of  $T_d$  will serve nicely in calculating  $f_w(T_d, P)$ ”. A question then emerges concerning what should be considered reasonable for a rough approximation. In the case that relative humidity is high, the air temperature measured by an EC system may be close enough to be a rough estimation of  $T_d$ , however this may be considered unreasonable in the sense of a numerical analysis because an error range is unknown. And in case when relative humidity is low, this approximation could differ from the true dewpoint temperature by more than 10 °C, making it even more unreasonable in terms of atmospheric physics. Thus another approach is proposed by Buck (1981) for calculating a more accurate approximation of  $T_d$  as described below.

## A.2 Approach to Approximation of $T_d$ for the Enhancement Factor

For general use to calculate dewpoint temperature ( $T_{d\_gu}$  where subscript *gu* indicates general use), Buck (1981) recommended the following equation:

$$e_s(T_{d\_gu}, P) = 0.61121 \exp\left(\frac{17.502T_{d\_gu}}{T_{d\_gu} + 240.97}\right) f_w(P) \quad (\text{A-7})$$

Where:

$$f_w(P) = 1.0007 + 3.46 \times 10^{-5} P \quad (\text{A-8})$$

Unlike  $f_w(T_d, P)$  in equation (A-5),  $f_w(P)$  in equation (A-7) does not include a quadratic term of dewpoint temperature,  $T_{d\_gu}$  can be analytically expressed in terms of saturation water pressure and total pressure as

$$T_{d\_gu} = \frac{240.97 \{ \ln e_s - \ln [0.61121 f_w(P)] \}}{17.502 - \{ \ln e_s - \ln [0.61121 f_w(P)] \}} \quad (\text{A-9})$$

Because in equation (A-7) the saturation water vapor equation for pure water has an error limit of  $\pm 0.2\%$  in a temperature range of  $-20$  to  $+50$  °C and a normal range of surface-layer pressures [see Figure 1 and Table 1 in Buck (1981)], and because the enhancement factor also has an error limit of  $\pm 0.2\%$  in a temperature range of  $-40$  to  $+50$  °C [see Figure 3 and Table 3 in Buck (1981)], the dewpoint temperature for general use ( $T_{d\_gu}$ ) as calculated using equation (10) has known an error limit and can be considered a relatively accurate approximation for  $T_d$  in equation (A-6).

## A.3 Dewpoint Temperature Equation

Now that a good approximation for  $T_d$  is found,  $T_{d\_gu}$  from equation (A-9) may be substituted for  $T_d$  into equation (A-6). The resulting enhancement factor can then be used along with measured water vapor pressure and total pressure to give a more accurate dewpoint temperature ( $T_d$ ):

$$T_d = \begin{cases} \frac{238.88 \{ \ln e_s - \ln [0.61121 f_w(T_{d\_gu}, P)] \}}{17.368 - \{ \ln e_s - \ln [0.61121 f_w(T_{d\_gu}, P)] \}} & T_{d\_gu} \geq 0 \\ \frac{247.15 \{ \ln e_s - \ln [0.61121 f_w(T_{d\_gu}, P)] \}}{17.966 - \{ \ln e_s - \ln [0.61121 f_w(T_{d\_gu}, P)] \}} & T_{d\_gu} < 0 \end{cases} \quad (\text{A-10})$$

Note that in this equation, the variable of  $T_{d\_gu}$  instead of  $T_d$  in equation (A-5) is used to judge the boundary for use of two sub-equations, although using either variable for the boundary should yield nearly the same result since according to Buck (1981),  $T_d$  and  $T_{d\_gu}$  should be within  $0.1$  °C of each other as long as the magnitude of dewpoint temperature is less than  $50$  °C. Furthermore, the two sub-equations in equation (5) have the same accuracy around  $0$  °C dewpoint temperature for a range of  $-1$  to  $+1$  °C [see Figure 1 in Buck (1981)] and are effectively interchangeable from  $-1$  to  $+1$  °C. Because the two sub-equations in equation (A-10) are simply rearrangements of the two sub-equations in equation (A-5), respectively, the two sub-equations in equation (A-10) also must be interchangeable from  $-1$  to  $1$  °C.

## A.4 Online Flux Program

The data-logger program calculates  $T_d$  by first converting measured water vapor density to water vapor pressure,  $e$  (equation A-1). Because dewpoint

temperature is the temperature at which  $e$  becomes the saturated vapor pressure,  $e_s$ , we use the value of  $e$  from the IRGA in place of  $e_s$  in equation (A-10).

## **A.5 Reference**

Buck, A. L.: 1981, "New equations for computing vapor pressure and enhancement factor", J. Applied Meteorol., 20:1527-1532.



# Appendix B. Coordinate Rotations: Double Rotation Method

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The covariance of vertical wind with a scalar (for example, heat, water vapor, or CO<sub>2</sub>) yields a scalar flux. The covariance of vertical wind with horizontal wind along with air density, gives momentum flux. If the measured vertical wind is not truly normal to the surface of interest, the flux estimates are in error (Kaimal and Haugen 1969). Flow velocities measured by a three-dimensional anemometer are defined in an instrument coordinate system. Although the instrument coordinate system is defined accurately in the manufacturing process by precision machining, and field mounting may be done carefully to align the sensor's vertical axis ( $z_m$  axis) to be perpendicular to the field surface, it is almost impossible for the  $z_m$  axis to be aligned perfectly. Some degree of leveling errors will be present and surface undulation may occur. Tilts of the order of a degree could cause errors in excess of 100% for momentum flux (Kraus 1968). Kaimal and Haugen (1969) further confirmed that large errors can occur in the measurement of momentum flux unless the sensors are vertically aligned and horizontally leveled with a great accuracy (at least  $\pm 0.1^\circ$ ). The errors caused by tilt in estimates of flux can be corrected using the mathematical method of coordinate transforms based on the physical process of turbulent flows (mean vertical velocity of dry air is zero).

## B.1 Matrix Transformation of Instrument to Flow Coordinate System

Let us define a 3D right-handed orthogonal instrument coordinate system where  $u_m$ ,  $v_m$ , and  $w_m$  are the orthogonal components of the 3D wind vector reported by the sonic anemometer. Now suppose that it is more convenient to report the same vector but using components on another orthogonal coordinate system that we will call the flow coordinate system, where the  $u$ -axis is parallel to the mean wind vector over some period of time (i.e., the streamwise vector),  $v$  is the mean crosswind component, and  $w$  is the vertical component. This is possible using the matrix transformation presented in B-1. This transformation performs the following functions: 1) the instrument coordinate system is rotated about the  $w_m$ -axis by a counterclockwise angle  $\gamma$  as viewed against the  $w_m$  direction to the 1<sup>st</sup> rotated coordinate system. If components are reported at this intermediary stage,  $u_1$ ,  $v_1$ ,  $w_1$  are used, where subscript "1" indicates the value of variable after the 1<sup>st</sup> rotation; 2) next the coordinate system is rotated about the  $v_1$ -axis by a counterclockwise angle  $\alpha$  as viewed down the  $v_1$  axis. This results in the 2<sup>nd</sup> rotated system, where  $u_2$ ,  $v_2$ , and  $w_2$  are the components of the wind vector after the 2<sup>nd</sup> rotation; 3) finally the 2<sup>nd</sup> rotated system is rotated about the  $u_2$ -axis by a counterclockwise angle  $\beta$  as viewed against  $u_2$  axis, resulting in the final flow coordinate system ( $u$ ,  $v$ ,  $w$ ).

**NOTE**

The angle rotations from the instrument coordinate system to natural flow coordinate system are used inconsistently in the literature. Tanner and Thurtell (1969) used counterclockwise rotations about vertical and streamwise axes and clockwise rotation about lateral axis. Wilczak et al (2001) used clockwise rotations for all of the three axes. The online flux program uses the rotation convention of Wilczak et al (2001) regardless of whether the double rotation or the planar fit method is used.

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & \sin \beta \\ 0 & -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \cos \alpha & 0 & -\sin \alpha \\ 0 & 1 & 0 \\ \sin \alpha & 0 & \cos \alpha \end{pmatrix} \begin{pmatrix} \cos \gamma & \sin \gamma & 0 \\ -\sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} u_m \\ v_m \\ w_m \end{pmatrix} \quad (\text{B-1})$$

$$= \mathbf{U}(\beta)\mathbf{V}(\alpha)\mathbf{W}(\gamma) \begin{pmatrix} u_m \\ v_m \\ w_m \end{pmatrix} = \mathbf{U}(\beta)\mathbf{V}(\alpha) \begin{pmatrix} u_1 \\ v_1 \\ w_1 \end{pmatrix} = \mathbf{U}(\beta) \begin{pmatrix} u_2 \\ v_2 \\ w_2 \end{pmatrix}$$

Where  $\mathbf{U}(\beta)$ ,  $\mathbf{V}(\alpha)$ , and  $\mathbf{W}(\gamma)$  are the three 3 x 3 matrices shown in the first equation of (B-1). The rotations are performed sequentially as shown in the second equation of (B-1). The 2<sup>nd</sup> and 3<sup>rd</sup> rotation angles are defined with respect to the coordinates after the preceding rotation.

## B.2 Natural Wind Coordinated System

A 3D right-handed natural wind coordinate system has the  $u$ -axis parallel to the mean or streamwise flow; thus the mean wind components along  $v$ -axis ( $\bar{v}$ ) and  $w$ -axis ( $\bar{w}$ ) are zero, as shown in FIGURE B-1.

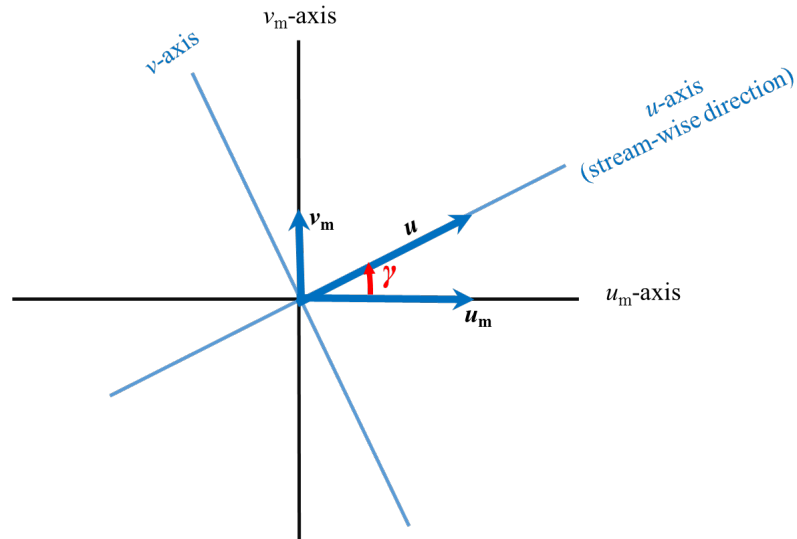


FIGURE B-1. As viewed down the  $z_m$  and  $z$  axes and assuming the vertical wind component is zero, horizontal wind components  $v_m$  and  $u_m$  are measured in the instrument coordinate system and then rotated by angle  $\gamma$ , yielding the streamwise wind velocity vector,  $u$ . The  $u$  and  $v$  axes of the flow coordinate system are also shown.

Because velocity in the  $v$  direction (orthogonal to  $u$  direction) is zero and flow is horizontally homogenous, the tilt in the  $v$  direction causes less error than in the  $u$  direction. Additionally, the calculation of the 3<sup>rd</sup> rotation angle assumes the following:

$$\overline{w_2 v_2} = 0$$

which may not necessarily be true in field conditions and introduces more uncertainties; therefore, the third rotation is not recommended (Wilczak et al. 2001). The algorithm for the first two rotations is given as follows:

angle  $\gamma$  in FIGURE B-1 can be approximated by:

$$\gamma = \arctan\left(\frac{\overline{v_m}}{\overline{u_m}}\right) \quad (\text{B-2})$$

This angle is the mean wind direction of 0 to 360° that is output from the CRBasic instruction of WindVector used in the data logger. The anticlockwise angle  $\alpha$  around the  $v_1$ -axis is given by:

$$\alpha = -\arctan \frac{\overline{w_1}}{\overline{u_1}} = -\arctan \frac{\overline{w_m}}{\overline{u_m} \cos \gamma + \overline{v_m} \sin \gamma} \quad (\text{B-3})$$

The CRBasic function ATN2() is used to calculate (B-3) and return an angle in the range of  $\pm 180^\circ$ . The result, however, must be further constrained to the range of  $\pm 90^\circ$  since relative to  $\gamma$ , the range of this angle is narrower and should be within  $\pm 90^\circ$ .

According to equation (B-1), the first two rotations are expressed as:

$$\begin{bmatrix} u_2 \\ v_2 \\ w_2 \end{bmatrix} = \begin{bmatrix} \cos \alpha \cos \gamma & \cos \alpha \sin \gamma & -\sin \alpha \\ -\sin \gamma & \cos \gamma & 0 \\ \sin \alpha \cos \gamma & \sin \alpha \sin \gamma & \cos \alpha \end{bmatrix} \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix} = \mathbf{R}_2 \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix} \quad (\text{B-4})$$

## B.2.1 Covariance of Momentum Variables after Coordinate Rotation

Using matrix operations, the covariance of the momentum variables can be reasonably found as follows:

From (B-4), the mean terms can be written as:

$$\begin{bmatrix} \overline{u_2} \\ \overline{v_2} \\ \overline{w_2} \end{bmatrix} = \mathbf{R}_2 \begin{bmatrix} \overline{u_m} \\ \overline{v_m} \\ \overline{w_m} \end{bmatrix} = \begin{bmatrix} \cos \alpha (\overline{u_m} \cos \gamma + \overline{v_m} \sin \gamma) - \overline{w_m} \sin \alpha \\ 0 \\ \sin \alpha (\overline{u_m} \cos \gamma + \overline{v_m} \sin \gamma) + \overline{w_m} \cos \alpha \end{bmatrix} \quad (\text{B-5})$$

And the fluctuation terms can be written as:

$$\begin{bmatrix} u'_2 \\ v'_2 \\ w'_2 \end{bmatrix} = \mathbf{R}_2 \begin{bmatrix} u'_m \\ v'_m \\ w'_m \end{bmatrix} \quad (\text{B-6})$$

Self-multiplication generates:

$$\begin{bmatrix} u'_2 \\ v'_2 \\ w'_2 \end{bmatrix} \begin{bmatrix} u'_2 & v'_2 & w'_2 \end{bmatrix} = \mathbf{R}_2 \begin{bmatrix} u'_m \\ v'_m \\ w'_m \end{bmatrix} \begin{bmatrix} u'_m & v'_m & w'_m \end{bmatrix} \mathbf{R}_2^T \quad (\text{B-7})$$

Applying Reynolds averaging yields:

$$\begin{bmatrix} \overline{u'^2_2} & \overline{u'_2 v'_2} & \overline{u'_2 w'_2} \\ \overline{u'_2 v'_2} & \overline{v'^2_2} & \overline{v'_2 w'_2} \\ \overline{u'_2 w'_2} & \overline{v'_2 w'_2} & \overline{w'^2_2} \end{bmatrix} = \mathbf{R}_2 \begin{bmatrix} \overline{u'^2_m} & \overline{u'_m v'_m} & \overline{u'_m w'_m} \\ \overline{u'_m v'_m} & \overline{v'^2_m} & \overline{v'_m w'_m} \\ \overline{u'_m w'_m} & \overline{v'_m w'_m} & \overline{w'^2_m} \end{bmatrix} \mathbf{R}_2^T \quad (\text{B-8})$$

See Appendix B.3, *Extended Equations* (p. B-5), for the expansion of these matrix operations for CRBasic coding.

## B.2.2 Covariance of a Scalar Variable and Momentum Variable After Second Coordinate Rotation

The covariance of a scalar variable,  $Q$ , and each rotated wind variable is found by multiplying the fluctuation of the scalar,  $Q'$ , to equation B-6, to give equation B-9:

$$Q' \begin{bmatrix} u'_2 \\ v'_2 \\ w'_2 \end{bmatrix} = \mathbf{R}_2 Q' \begin{bmatrix} u'_m \\ v'_m \\ w'_m \end{bmatrix} \quad (\text{B-9})$$

Then by applying Reynolds averaging:

$$\begin{bmatrix} \overline{Q' u'_2} \\ \overline{Q' v'_2} \\ \overline{Q' w'_2} \end{bmatrix} = \mathbf{R}_2 \begin{bmatrix} \overline{Q' u'_m} \\ \overline{Q' v'_m} \\ \overline{Q' w'_m} \end{bmatrix} = \begin{bmatrix} \cos \alpha \left( \overline{Q' u'_m} \cos \gamma + \overline{Q' v'_m} \sin \gamma \right) - \overline{Q' w'_m} \sin \alpha \\ -\overline{Q' u'_m} \sin \gamma + \overline{Q' v'_m} \cos \gamma \\ \sin \alpha \left( \overline{Q' u'_m} \cos \gamma + \overline{Q' v'_m} \sin \gamma \right) + \overline{Q' w'_m} \cos \alpha \end{bmatrix} \quad (\text{B-10})$$

### B.3 Extended Equations

The extended form of Equation (B-8) is given by:

$$\begin{bmatrix} \overline{u_2'^2} & \overline{u_2'v_2'} & \overline{u_2'w_2'} \\ \overline{u_2'v_2'} & \overline{v_2'^2} & \overline{v_2'w_2'} \\ \overline{u_2'w_2'} & \overline{v_2'w_2'} & \overline{w_2'^2} \end{bmatrix} = \begin{bmatrix} \cos \alpha \cos \gamma & \cos \alpha \sin \gamma & -\sin \alpha \\ -\sin \gamma & \cos \gamma & 0 \\ \sin \alpha \cos \gamma & \sin \alpha \sin \gamma & \cos \alpha \end{bmatrix} \begin{bmatrix} \overline{u_m'^2} & \overline{u_m'v_m'} & \overline{u_m'w_m'} \\ \overline{u_m'v_m'} & \overline{v_m'^2} & \overline{v_m'w_m'} \\ \overline{u_m'w_m'} & \overline{v_m'w_m'} & \overline{w_m'^2} \end{bmatrix} \begin{bmatrix} \cos \alpha \cos \gamma & -\sin \gamma & \sin \alpha \cos \gamma \\ \cos \alpha \sin \gamma & \cos \gamma & \sin \alpha \sin \gamma \\ -\sin \alpha & 0 & \cos \alpha \end{bmatrix} \quad (\text{B-11})$$

In Equation (B-11), the extended forms of variance terms in the matrix on the left hand side are, expressed in terms of the matrices on the right hand side:

$$\begin{cases} \overline{u_2'^2} = \cos^2 \alpha \left( \overline{u_m'^2} \cos^2 \gamma + \overline{v_m'^2} \sin^2 \gamma \right) + \overline{w_m'^2} \sin^2 \alpha + \overline{u_m'v_m'} \cos^2 \alpha \sin 2\gamma - \sin 2\alpha \left( \overline{u_m'w_m'} \cos \gamma + \overline{v_m'w_m'} \sin \gamma \right) \\ \overline{v_2'^2} = \overline{u_m'^2} \sin^2 \gamma + \overline{v_m'^2} \cos^2 \gamma - \overline{u_m'v_m'} \sin 2\gamma \\ \overline{w_2'^2} = \sin^2 \alpha \left( \overline{u_m'^2} \cos^2 \gamma + \overline{v_m'^2} \sin^2 \gamma \right) + \overline{w_m'^2} \cos^2 \alpha + \overline{u_m'v_m'} \sin^2 \alpha \sin 2\gamma + \sin 2\alpha \left( \overline{u_m'w_m'} \cos \gamma + \overline{v_m'w_m'} \sin \gamma \right) \end{cases} \quad (\text{B-12})$$

In Equation (B-11), the extended forms of covariance terms in the matrix of left hand side are expressed in terms of the matrices on the right hand side

$$\begin{cases} \overline{u_2'v_2'} = -\frac{1}{2} \left( \overline{u_m'^2} - \overline{v_m'^2} \right) \cos \alpha \sin 2\gamma + \overline{u_m'v_m'} \cos \alpha \cos 2\gamma + \sin \alpha \left( \overline{u_m'w_m'} \sin \gamma - \overline{v_m'w_m'} \cos \gamma \right) \\ \overline{u_2'w_2'} = \frac{1}{2} \sin 2\alpha \left[ \left( \overline{u_m'^2} \cos^2 \gamma + \overline{v_m'^2} \sin^2 \gamma \right) - \overline{w_m'^2} + \overline{u_m'v_m'} \sin 2\gamma \right] + \cos 2\alpha \left( \overline{u_m'w_m'} \cos \gamma + \overline{v_m'w_m'} \sin \gamma \right) \\ \overline{v_2'w_2'} = -\sin \alpha \left[ \frac{1}{2} \left( \overline{u_m'^2} - \overline{v_m'^2} \right) \sin 2\gamma - \overline{u_m'v_m'} \cos 2\gamma \right] - \cos \alpha \left( \overline{u_m'w_m'} \sin \gamma - \overline{v_m'w_m'} \cos \gamma \right) \end{cases} \quad (\text{B-13})$$

## B.4 References

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# Appendix C. Coordinate Rotations: Planar Fit Method

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## C.1 Planar Fit

The planar fit method of coordinate rotations is based on Wilczak et al. (2001). The method is used to transform the measured wind velocities in the right-handed measurement coordinate system of a sonic anemometer ( $u_m, v_m, w_m$ ), where subscript  $m$  indicates measurement coordinate system, to the natural wind coordinate system ( $u, v, w$ ) if the three rotations are performed.

The first and the second rotations in the planar fit are related to flux; that is, both rotations transform the measured wind velocities to a coordinate system with the horizontal coordinate plane parallel to the natural wind plane. The algorithm used for the planar fit rotations mathematically describes two counterclockwise coordinate rotations, first about the  $u_m$ -axis by an angle  $\beta$ , and second about the intermediate  $v_l$ -axis by an angle  $\alpha$ , where the subscript  $l$  indicates the variable after the 1<sup>st</sup> rotation. The expression of measured fluxes in this coordinate system avoids the errors in fluxes due to the tilt of the sonic anemometer vertical axis away from the vertical axis of the natural wind flow coordinate system.

The angle  $\alpha$  is the angle between the instrument  $u_m$ -axis and the  $u$ - $v$  plane of natural wind (i.e., the tilt angle of the instrument vertical  $w_m$ -axis away from the natural wind vertical axis in the instrument  $u_m$ - $w_m$  plane), where  $\alpha$  increases clockwise in the 360° domain, which means a clockwise rotation for angle  $\alpha$  is positive and a counterclockwise rotation is negative. The angle  $\beta$  is the angle between the instrument  $v_m$ -axis and the  $u$ - $v$  plane (i.e., the tilt angle of the  $w_m$ -axis away from the natural wind vertical axis in the instrument  $v_m$ - $w_m$  plane), where  $\beta$  increases counterclockwise in the 360° domain, which means a clockwise rotation for angle  $\beta$  is negative and a counterclockwise rotation is positive.

Even if the sonic anemometer is well secured and leveled in the field, wind may force the mounting structure and sonic anemometer to tilt, especially if the tower is tall (greater than 3 m, for example). The degree of the inclination depends on the momentum load determined mainly by wind speed. Furthermore, the natural  $u$ - $v$  plain relative to a fixed plain varies if the field undulates and has a slope that varies from different directions. Therefore, in a given field station, the two coordinate rotation angles should be defined as a function of wind direction and wind speed. However, it is not practical to determine the angles for every possible wind direction and speed, so instead, the angles are defined for certain sectors of wind direction using data averaged over a time interval (for example, 30 min), and the dependence on wind speed is not considered.

For the online planar fit algorithm, four sectors or ranges of wind direction *in the instrument coordinate system* are used. The boundaries of sectors match the boundaries of sectors in “horizontal orientation of the sonic anemometer” for data quality classification by Foken et al. (2012). Using statistically sufficient data (see models [37] to [48] in Wilczak et al. [2001]) from the four direction sectors, a user can calculate the two angles for the four sectors, respectively.

The four ranges are given below along with the angle names used in the program:

Sector 1: [0, 60] and [300, 360]

$\alpha_{60\_300}$

$\beta_{60\_300}$

Sector 2: (60, 170]

$\alpha_{60\_170}$

$\beta_{60\_170}$

Sector 3: (170, 190)

$\alpha_{170\_190}$

$\beta_{170\_190}$

Sector 4: [190, 300)

$\alpha_{190\_300}$

$\beta_{190\_300}$

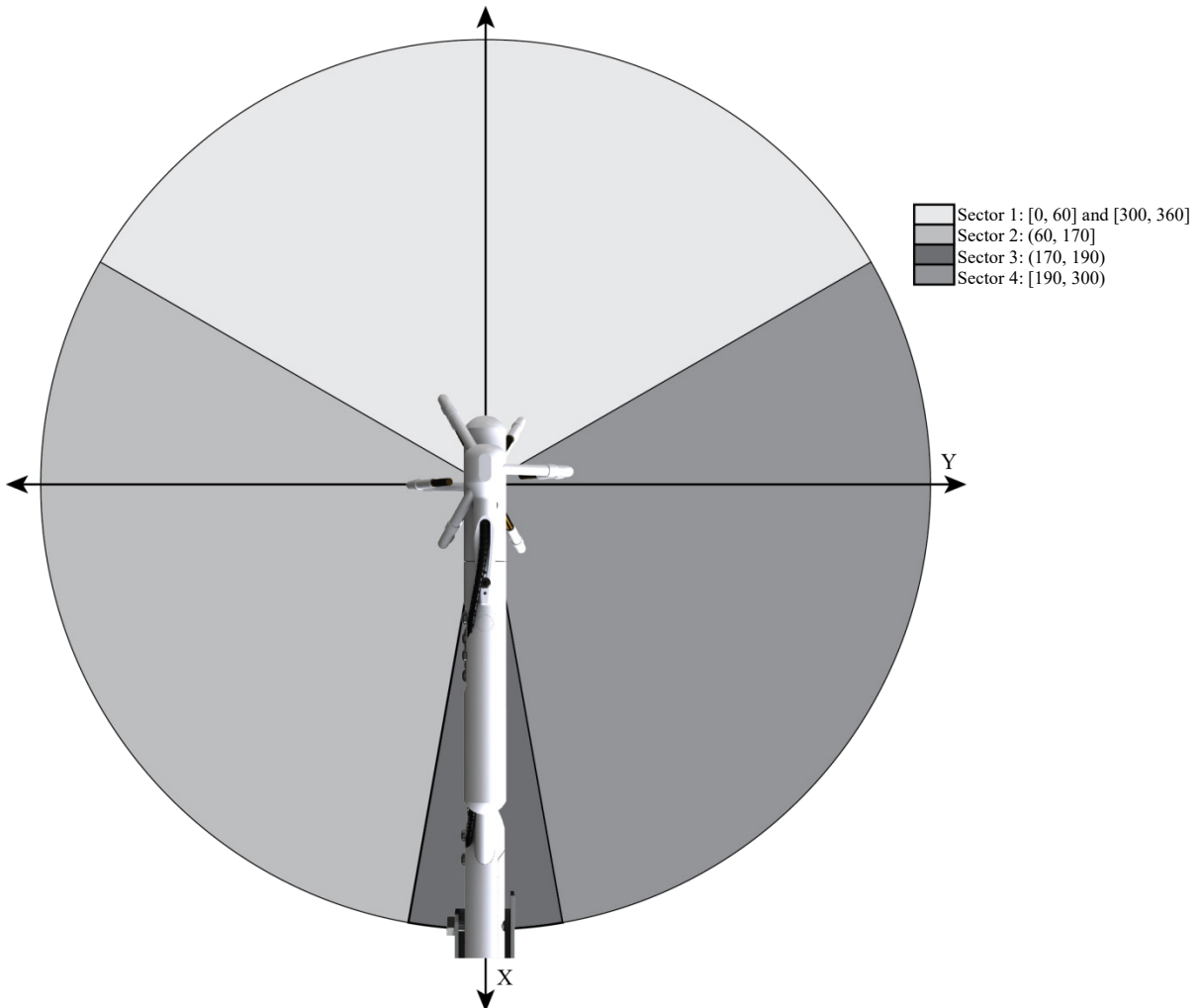


FIGURE C-1. Wind direction sectors for which planar fit angles are found by the user and entered into the program.



## C.2 Algorithm

### C.2.1 Variables and Model

To use the planar fit method, the user must independently (using post-processing software and time-series data for an appropriate length of time) determine the angles for each wind sector and enter these values with the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)). The online flux program will then select the appropriate angles based on the mean wind direction during the averaging interval. The CRBasic code that corresponds to this is as follows:

If (wind direction  $\leq 60$ ) OR (wind direction  $\geq 300$ ) then:

$$\begin{aligned}\alpha &= \alpha_{60\_300} \\ \beta &= \beta_{60\_300}\end{aligned}$$

If ( $60 < \text{wind direction} \leq 170$ ) then:

$$\begin{aligned}\alpha &= \alpha_{60\_170} \\ \beta &= \beta_{60\_170}\end{aligned}$$

If ( $170 < \text{wind direction} < 190$ ) then:

$$\begin{aligned}\alpha &= \alpha_{170\_190} \\ \beta &= \beta_{170\_190}\end{aligned}$$

If ( $190 < \text{wind direction} < 300$ ) then:

$$\begin{aligned}\alpha &= \alpha_{190\_300} \\ \beta &= \beta_{190\_300}\end{aligned}$$

Given a pitch angle of  $\alpha$  and a roll angle of  $\beta$ , the three orthogonal wind velocities ( $u$ ,  $v$ ,  $w$ ) after the two rotations can be expressed in terms of the two angles ( $\alpha$ ,  $\beta$ ) and three directly measured wind velocities ( $u_m$ ,  $v_m$ ,  $w_m$ ) as:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \cos \alpha & 0 & -\sin \alpha \\ 0 & 1 & 0 \\ \sin \alpha & 0 & \cos \alpha \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & \sin \beta \\ 0 & -\sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix} \quad (\text{C-1})$$

Further:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \sin \beta & -\sin \alpha \cos \beta \\ 0 & \cos \beta & \sin \beta \\ \sin \alpha & -\cos \alpha \sin \beta & \cos \alpha \cos \beta \end{bmatrix} \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix} = \mathbf{R}_p \begin{bmatrix} u_m \\ v_m \\ w_m \end{bmatrix} \quad (\text{C-2})$$

Where  $\mathbf{R}_p$  is the 3 x 3 matrix in (C-2), and subscript  $p$  indicates the planar fit approach for the rotations.

### C.2.2 Covariance of Momentum Variables After Two Coordinate Rotations

Using matrix operations, the covariance of the momentum variables can be reasonably found as follows.

Using equation (C-2), we can express the mean terms as:

$$\begin{bmatrix} \bar{u} \\ \bar{v} \\ \bar{w} \end{bmatrix} = \mathbf{R}_p \begin{bmatrix} \bar{u}_m \\ \bar{v}_m \\ \bar{w}_m \end{bmatrix} = \begin{bmatrix} \bar{u}_m \cos \alpha + \sin \alpha (\bar{v}_m \sin \beta - \bar{w}_m \cos \beta) \\ \bar{v}_m \cos \beta + \bar{w}_m \sin \beta \\ \bar{u}_m \sin \alpha - \cos \alpha (\bar{v}_m \sin \beta - \bar{w}_m \cos \beta) \end{bmatrix} \quad (\text{C-3})$$

and fluctuation terms as:

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \mathbf{R}_p \begin{bmatrix} u'_m \\ v'_m \\ w'_m \end{bmatrix} \quad (\text{C-4})$$

Self-multiplication generates:

$$\begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} \begin{bmatrix} u' & v' & w' \end{bmatrix} = \mathbf{R}_p \begin{bmatrix} u'_m \\ v'_m \\ w'_m \end{bmatrix} \begin{bmatrix} u'_m & v'_m & w'_m \end{bmatrix} \mathbf{R}_p^T \quad (\text{C-5})$$

Applying Reynolds averaging yields:

$$\begin{bmatrix} \overline{u'^2} & \overline{u'v'} & \overline{u'w'} \\ \overline{u'v'} & \overline{v'^2} & \overline{v'w'} \\ \overline{u'w'} & \overline{v'w'} & \overline{w'^2} \end{bmatrix} = \mathbf{R}_p \begin{bmatrix} \overline{u_m'^2} & \overline{u'_m v'_m} & \overline{u'_m w'_m} \\ \overline{u'_m v'_m} & \overline{v_m'^2} & \overline{v'_m w'_m} \\ \overline{u'_m w'_m} & \overline{v'_m w'_m} & \overline{w_m'^2} \end{bmatrix} \mathbf{R}_p^T \quad (\text{C-6})$$

These matrix operations can then be expanded to be used in the online flux program. See Appendix C.3, *Extended Equations (p. C-6)*, for the coding.

### C.2.3 Covariance of a Scalar Variable with Momentum Variable After Planar Fit Coordinate Rotation

The covariance of a scalar variable,  $Q$ , and each rotated wind variable is found by multiplying the fluctuation of the scalar,  $Q'$ , to equation (C-4):

$$Q' \begin{bmatrix} u' \\ v' \\ w' \end{bmatrix} = \mathbf{R}_p Q' \begin{bmatrix} u'_m \\ v'_m \\ w'_m \end{bmatrix} \quad (\text{C-7})$$

Applying Reynolds averaging yields:

$$\begin{bmatrix} \overline{Q'u'} \\ \overline{Q'v'} \\ \overline{Q'w'} \end{bmatrix} = \mathbf{R}_p \begin{bmatrix} \overline{Q'u'_m} \\ \overline{Q'v'_m} \\ \overline{Q'w'_m} \end{bmatrix} = \begin{bmatrix} \overline{Q'u'_m} \cos \alpha + \sin \alpha \left( \overline{Q'v'_m} \sin \beta - \overline{Q'w'_m} \cos \beta \right) \\ \overline{Q'v'_m} \cos \beta + \overline{Q'w'_m} \sin \beta \\ \overline{Q'u'_m} \sin \alpha - \cos \alpha \left( \overline{Q'v'_m} \sin \beta - \overline{Q'w'_m} \cos \beta \right) \end{bmatrix} \quad (\text{C-8})$$

### C.3 Extended Equations

The extended form of Equation (C-6) is given by:

$$\begin{bmatrix} \overline{u'^2} & \overline{u'v'} & \overline{u'w'} \\ \overline{u'v'} & \overline{v'^2} & \overline{v'w'} \\ \overline{u'w'} & \overline{v'w'} & \overline{w'^2} \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \sin \beta & -\sin \alpha \cos \beta \\ 0 & \cos \beta & \sin \beta \\ \sin \alpha & -\cos \alpha \sin \beta & \cos \alpha \cos \beta \end{bmatrix} \begin{bmatrix} \overline{u_m'^2} & \overline{u_m'v_m'} & \overline{u_m'w_m'} \\ \overline{u_m'v_m'} & \overline{v_m'^2} & \overline{v_m'w_m'} \\ \overline{u_m'w_m'} & \overline{v_m'w_m'} & \overline{w_m'^2} \end{bmatrix} \begin{bmatrix} \cos \alpha & 0 & \sin \alpha \\ \sin \alpha \sin \beta & \cos \beta & -\cos \alpha \sin \beta \\ -\sin \alpha \cos \beta & \sin \beta & \cos \alpha \cos \beta \end{bmatrix} \quad (C-9)$$

In equation (C-9), the extended forms of variance terms in the matrix on the left hand side are expressed in terms of the matrices on the right hand side:

$$\begin{cases} \overline{u'^2} = \overline{u_m'^2} \cos^2 \alpha + \sin^2 \alpha \left( \overline{v_m'^2} \sin^2 \beta - \overline{v_m'w_m'} \sin 2\beta + \overline{w_m'^2} \cos^2 \beta \right) + \sin 2\alpha \left( \overline{u_m'v_m'} \sin \beta - \overline{u_m'w_m'} \cos \beta \right) \\ \overline{v'^2} = \overline{v_m'^2} \cos^2 \beta + \overline{v_m'w_m'} \sin 2\beta + \overline{w_m'^2} \sin^2 \beta \\ \overline{w'^2} = \overline{u_m'^2} \sin^2 \alpha + \cos^2 \alpha \left( \overline{v_m'^2} \sin^2 \beta - \overline{v_m'w_m'} \sin 2\beta + \overline{w_m'^2} \cos^2 \beta \right) - \sin 2\alpha \left( \overline{u_m'v_m'} \sin \beta - \overline{u_m'w_m'} \cos \beta \right) \end{cases} \quad (C-10)$$

In equation (C-9), the extended forms of covariance terms in the matrix of the left hand side are expressed in terms of the matrices on the right hand side:

$$\begin{cases} \overline{u'v'} = \sin \alpha \left[ \frac{1}{2} \left( \overline{v_m'^2} - \overline{w_m'^2} \right) \sin 2\beta - \overline{v_m'w_m'} \cos 2\beta \right] + \cos \alpha \left( \overline{u_m'v_m'} \cos \beta + \overline{u_m'w_m'} \sin \beta \right) \\ \overline{u'w'} = \frac{1}{2} \sin 2\alpha \left( \overline{u_m'^2} - \overline{v_m'^2} \sin^2 \beta - \overline{w_m'^2} \cos^2 \beta + \overline{v_m'w_m'} \sin 2\beta \right) - \cos 2\alpha \left( \overline{u_m'v_m'} \sin \beta - \overline{u_m'w_m'} \cos \beta \right) \\ \overline{v'w'} = -\cos \alpha \left[ \frac{1}{2} \left( \overline{v_m'^2} - \overline{w_m'^2} \right) \sin 2\beta - \overline{v_m'w_m'} \cos 2\beta \right] + \sin \alpha \left( \overline{u_m'v_m'} \cos \beta + \overline{u_m'w_m'} \sin \beta \right) \end{cases} \quad (C-11)$$

## C.4 References

- Tanner, C. B. and Thurtell, G. W.: 1969, “Anemoclinometer measurements of Reynolds stress and heat transport in the atmospheric surface layer”, Research and Development Tech. Report ECOM 66-G22-F.
- Wilczak, J.M., S. P. Oncley, S. A. Stage.: 2001, “Sonic Anemometer tilt correction algorithm”, *Boundary-Layer Meteorol.* 99:127-150.
- Foken et al. (2012) “Eddy Covariance: A Practical Guide to Measurement and Data Analysis” by Aubinet, Vesala, and Papale from Springer. This book consists of chapters that are written by specialists in the field. Chapter 4 titled “Corrections and Data Quality Control”.

# Appendix D. Frequency Corrections

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## D.1 Introduction

The flux of any scalar (e.g., heat, CO<sub>2</sub>, or H<sub>2</sub>O) or momentum is a summed amount of the scalar or momentum through a unit area per unit time (e.g., g m<sup>-2</sup> s<sup>-1</sup> for H<sub>2</sub>O), and transported by eddies of various frequencies (i.e., various sizes and velocities). The relative contribution of flux as a function of eddy frequency results in a cospectrum for covariance. The total or net flux is found by integrating over this cospectrum. In order to generate an accurate cospectrum, a measurement system must be able to measure and process fluctuations at all frequencies that contribute to the flux. In practice, however, sensor measurements and digital processing methods cannot fully capture the instantaneous changes at all frequencies. The uncaptured changes related to larger eddies results in low frequency losses, and the uncaptured changes related to smaller eddies results in high frequency losses. Accounting for these frequency losses requires the corrections described herein.

## D.2 Frequency Loss

### D.2.1 High Frequency Loss

High frequency loss is caused by sensor response delay, signal averaging over the measurement path or volume (line/volume averaging), sensor separation, and low-pass filtering. A brief description of each of these causes is provided below.

*Response delay:* A sensor requires a finite amount of time to measure a stimulus. When fluctuations of a scalar or wind occur faster than this time, high frequency losses occur. The response delay is described using a time constant defined as the time the sensor requires to respond to 63.2% of a change in the input stimulus.

*Line/volume averaging:* Most sensors measure the change in a variable of interest over a linear measurement path (CSAT3) or measurement volume (KH20) and report its spatially averaged value over that path or volume at the measurement time. Such a sensor cannot accurately report a change in the variable at a scale of eddies smaller than the dimension of the path or volume, which attenuates the signal at high frequencies.

*Separation:* A covariance of wind velocity with CO<sub>2</sub> or H<sub>2</sub>O concentration is measured using two sensors: a sonic anemometer and an infrared gas analyzer (IRGA). In most two-sensor combinations, except for the IRGASON which integrates both sensors into a single head, the wind velocities and gas concentrations are measured separately in different measurement volumes. This means that a single eddy may be measured at different times by the two sensors when the eddy dimension is smaller than the separation, or when a large eddy boundary moves between the two sensors during measurement. This results in signal attenuation at high frequencies because the cross correlation of wind velocities to scalar variable decreases with increases in separation (Kaimal and Finnigan 1994). Another example of two separated sensors is to use a sonic anemometer and a fine-wire thermocouple (for example, FW05, FW1, and FW3) for sensible heat flux to measure covariance of wind velocity with air temperature.

*Low-pass filtering:* A low-pass filter of Finite Impulse Response (FIR) improves the data quality for spectral analysis by removing the aliasing effect on the pass-frequency band due to signals at higher frequencies (i.e., frequency stop-band), but sharply attenuates the signal beyond the user-selected bandwidth (i.e., frequency pass-band; Campbell Scientific, 2014). This attenuation helps reduce unwanted aliasing effect on the frequency pass-band, but it may also result in the loss of high frequency fluxes depending on the sampling rate and frequency pass-band.

**NOTE**

The EC100 electronics used with the IRGASON and the EC150/CSAT3A has five options for bandwidth (i.e., pass-band): 5, 10, 12.5, or 20 Hz. For each option, the filter attenuates the signals at frequencies beyond the bandwidth.

## D.2.2 Low Frequency Loss

Fluxes are typically calculated by taking a block average of the covariance and other related variables over a 30-minute or longer interval. The block averaging is a high-pass filter, which causes low-frequency loss (Kaimal et al., 1989).

## D.3 Model for Frequency Loss Corrections

The frequency loss of covariance is determined by the frequency losses of each variable from which the covariance is calculated. The correction for this loss is described using a general correction model for covariance of any two variables.

Suppose the measured covariance is given by:

$$\overline{(\alpha'w')}_r$$

Where  $\alpha$  can represent  $T$  for temperature ( $^{\circ}\text{C}$ ),  $\rho_{\text{co}_2}$  for partial  $\text{CO}_2$  density ( $\text{mg}\cdot\text{m}^{-3}$ ),  $\rho_{\text{h}_2\text{o}}$  for partial  $\text{H}_2\text{O}$  density ( $\text{g}\cdot\text{m}^{-3}$ ), or  $u$  (or  $v$ ) for horizontal wind speed ( $\text{m}\cdot\text{s}^{-1}$ );  $w$  is vertical wind speed ( $\text{m}\cdot\text{s}^{-1}$ ); prime is the departure of variable from its mean; over-bar denotes the block time average; and subscript  $r$  represents a variable after coordinate rotation correction. Then, the frequency-corrected covariance is given by:

$$\overline{(\alpha'w')}_{rf}$$

where subscript  $f$  indicates a variable after frequency correction and is defined as [eq. 1 in Moore (1986)]:

$$\overline{(\alpha'w')}_{rf} = \overline{(\alpha'w')}_r \left\{ \frac{\int_0^{\infty} C_{\alpha w}(f) df}{\int_0^{\infty} T_{\alpha w}(f) C_{\alpha w}(f) df} \right\} \quad (\text{D-1})$$

where other variables are defined as follows:

$f$  – cyclic frequency

$C_{\alpha w}(f)$  – cospectrum of  $\alpha$  with  $w$ , which is the distribution of covariance of  $\alpha$  and  $w$  as a function of frequency.

$T_{aw}(f)$  – transfer function, defined as the relative response to a measured signal of wind or scalar at  $f$ , ranging from 0 for no response to 1 for full response. The transfer function here is the total transfer function that is the combined system response of all sensors and digital processors to report the signals of covariance of  $\alpha$  with  $w$ . It is a product of all sub-transfer functions (see Appendix D.8, *Sub-Transfer Functions* (p. D-12)).

The term in the curly brackets is defined as a frequency correction factor. Evaluating this factor requires determination of the total transfer function and the cospectrum within the integration. The total transfer function is a multiplication of sub-transfer functions (see Appendix D.8, *Sub-Transfer Functions* (p. D-12)). A sub-transfer function is covariance-specific, depending on flow aerodynamics, sensor configuration, and data processing method. The cospectrum is also covariance-specific, depending on aerodynamic height, wind speed, and atmospheric stability in the surface layer (see Appendix D.6, *Surface Layer Atmospheric Stability* (p. D-8)).

## D.4 Covariance Variables Requiring Frequency Corrections

This section lists the covariance variables that require frequency corrections.

### D.4.1 Momentum Covariance

Rotated wind components including  $u$ ,  $v$ , and  $w$  are derived from the sonic anemometer. The covariance of these variables shown below require frequency correction:

$$\overline{(v'w')}_r \text{ and } \overline{(u'w')}_r$$

Note that both of these covariances are used for calculating friction velocity (a scaling parameter in the surface layer).

### D.4.2 Sonic Temperature Related Covariance

The following covariances are from measurements from the sonic anemometer and IRGA and require frequency correction:

$$\overline{(T_s'w')}_r \text{ and } \overline{(T_c'w')}_r$$

where  $T_s$  is sonic temperature and  $T_c$  is air temperature calculated from sonic temperature, water vapor density, and pressure. The data logger program calculates sonic buoyancy flux,  $\overline{(T_s'w')}_r$ , each half hour and then applies the sonic sensible heat flux (SND) correction to convert the result to buoyancy flux. The SND correction requires inputs such as the mean water vapor as measured by the IRGA and air density, which requires mean air temperature. The mean air temperature may come from the EC100's temperature probe in the case of the EC150/CSAT3A, or from  $T_c$  in the case of the IRGASON since the colocated measurements allow for time series calculation of  $T_c$  from  $T_s$  and water vapor density.



**NOTE**

$T_c$  is considered the most accurate since it does not suffer from solar heating or radiative cooling. However,  $T_c$  can only be calculated using an IRGASON since the sonic temperature and water vapor density measurements must be made in the exact same volume. Pressure in the sample volume is also required, but it is assumed that there is negligible difference between the pressure in the sample volume and the pressure measured by the EC100's barometer.

### D.4.3 Air Temperature Related Covariance

Similar to sonic temperature, covariances from measurements of air temperature from a fine-wire thermocouple such as the FW05, FW1, and FW3 (hereafter referred as FW), also should be corrected.

$$\left( \overline{T'_{FW} w'} \right)_r$$

where  $T_{FW}$  is air temperature and subscript FW indicates a fine-wire thermocouple measurement.

### D.4.4 CO<sub>2</sub> and H<sub>2</sub>O Related Covariance

Covariances of CO<sub>2</sub> or H<sub>2</sub>O (measured by the IRGA) with vertical wind (measured by the sonic anemometer) must be corrected.

$$\left( \overline{\rho'_{CO_2} w'} \right)_r, \left( \overline{\rho'_{H_2O} w'} \right)_r$$

where  $\rho_{CO_2}$  is the mass density of CO<sub>2</sub>, and  $\rho_{H_2O}$  is mass density of H<sub>2</sub>O.

## D.5 Sensor Configuration and Separation Variables

Sensor configuration variables, which are required for determining frequency corrections used in sub-transfer functions that lead to the overall transfer function in Equation D-1, are described in this section and include descriptors such as the measurement path dimensions of the sonic anemometer and gas analyzer, sensor separation between the sonic anemometer and gas analyzer, and the diameter of the fine-wire thermocouple.

All of these configuration variables are set inside the program. Some of the variables, such as those dealing with sensor separation, depend on how the sensors are installed at a site; following installation, the variables should be measured, recorded, and entered into the program through the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)).

### D.5.1 Path Length Variables

For the CSAT3A or IRGASON sonic anemometer, the path length,  $l_{pt\_CSAT}$ , is equal to 0.11547 m. The subscript *pt* indicates path.

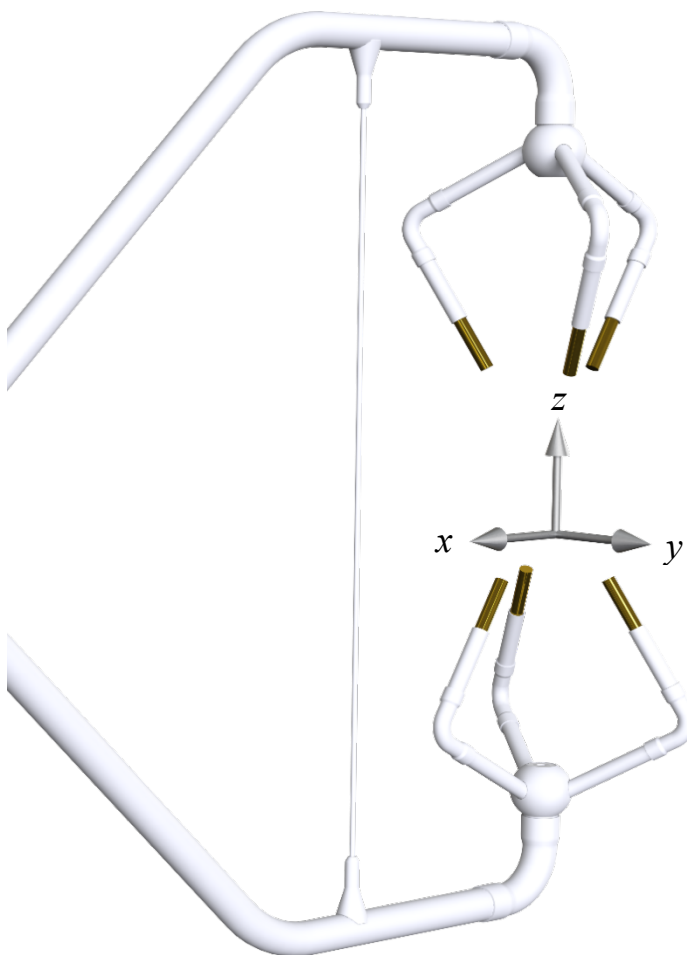
For the EC150 or IRGASON gas analyzer, the path length,  $l_{pt\_IRGA}$ , is equal to 0.1531 m.

## D.5.2 Separation Variables

In order to find the separation variables, which are entered into the program through the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad (p. 12)*), the center of the gas analyzer measurement path relative to the sonic coordinate system (see FIGURE D-1 and FIGURE D-2) must be known. Determine of each of these variables as described below.

*IRGA Coord x* (reported as the datafield *separation\_x\_irga* in the Flux\_Notes output table) is the abscissa (x-coordinate) of the center of the gas analyzer optical path in the sonic coordinate system. It should be set to 0 m for the IRGASON and ranges from 0.041 to 0.091 m for the EC150 and CSAT3A, depending on the EC150's position in its standard mounting bracket. When an EC150 and CSAT3A are used, the program assumes a default value of 0.041 m, which corresponds to the furthest forward position of the EC150 in its standard mounting bracket.

*IRGA Coord y* (reported as the datafield *separation\_y\_irga* in the Flux\_Notes output table) is the ordinate (y-coordinate) of the center of the gas analyzer optical path in the sonic coordinate system. It should be set to 0 m for the IRGASON and ranges from 0.029 to 0.033 for the configuration of EC150 and CSAT3A, depending on the EC150's position in its standard mounting bracket. When an EC150 and CSAT3A are used, the program assumes a default value of 0.029 m, which corresponds to the furthest forward position of the EC150 in its standard mounting bracket.



*FIGURE D-1. The sonic coordinate system is shown with positive  $x$ ,  $y$ , and  $z$  axes. Note that the origin of the coordinate system should be exactly in the center of the sonic volume; as shown, the origin has been moved slightly downwards for convenience in displaying the positive  $z$ -axis.*

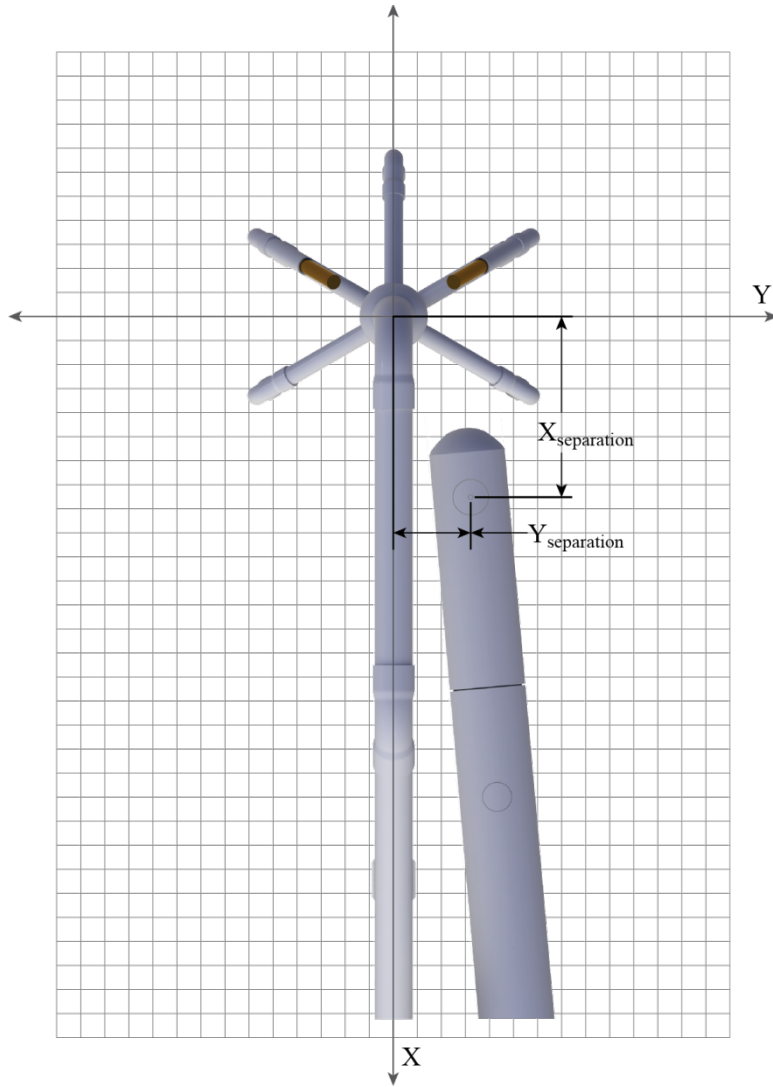


FIGURE D-2. The x and y spatial separations between a CSAT3A and EC150.

### D.5.3 Fine-Wire Thermocouple

If a fine wire thermocouple is used, additional configuration and separation variables must be entered into the program using the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)). These variables are described below.

#### Configuration Variable *FW Dim*

Depending on the fine wire thermocouple model being used, one of the following constants should be selected as the value for *FW Dim*, the configuration variable for dimension or diameter of the fine wire:

$FW05\_DIA = 1.27 \times 10^{-5}$  m for the diameter of the FW05

$FW1\_DIA = 2.54 \times 10^{-5}$  m for the diameter of the FW1

$FW3\_DIA = 7.62 \times 10^{-5}$  m fir the diameter of the FW3

**Separation variables**

*FW Coord x* (reported as the datafield *separation\_x\_FW* in the *Flux\_Notes* output table) is the abscissa (x-coordinate) of fine-wire thermocouple junction in the sonic coordinate system (see FIGURE D-1 and FIGURE D-2).

*FW Coord y* (reported as the datafield *separation\_y\_FW* in the *Flux\_Notes* output table) is the ordinate (y-coordinate) of fine-wire thermocouple junction in the sonic coordinate system.

The values for *FW Coord x* and *FW Coord y* are defaulted to 0.006m and 0.03259 m, respectively, for the IRGASON and CSAT3A. These correspond to the standard mounting and lengths of the FW05, FW1, and FW3. These values may be easily edited at the site using the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)).

## D.6 Surface Layer Atmospheric Stability

The cospectrum in model (D-1) depends on surface layer stability. The stability is defined as the ratio of aerodynamic height ( $z$ ) to Monin-Obukhov length ( $L$ ). This ratio is greater than 0 if surface layer is stable, 0 if neutral, and less than 0 if unstable. The cospectrum has different model forms for neutral/unstable and stable conditions (Kaimal et al., 1972). The stability is used as a variable in the cospectrum model for stable conditions, but not in the models for neutral or unstable conditions. The sub-sections below describe how the program calculates values for aerodynamic height and Monin-Obukhov length in order to determine stability. Stability during each averaging interval is reported in the *Flux\_Notes* output table as *stability\_zL*.

### D.6.1 Aerodynamic Height

Aerodynamic height is the measurement height ( $z_m$ ) minus zero displacement height, given by:

$$z = z_m - d \quad (\text{D-2})$$

where  $d$  is the zero displacement height.

1. *Measurement height* is the height of the center of the measurement volume of the eddy-covariance sensors above the surface of the ground. It is entered into the program as the variable *Meas Height* through the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)) following installation and whenever the sensor height is adjusted. In the *Flux\_Notes* output table, the last value to be entered is reported as *height\_measurement*.
2. *Displacement height* is the mean height at which the momentum flux is balanced by the momentum absorption into rough surface elements such as plants or the ground surface. In the case of flat, bare land, the height of aerodynamic ground surface is effectively zero. Inside a canopy, the aerodynamic surface is elevated to some height above the ground surface. This elevated height is defined as the displacement height.

The displacement height can be provided through three options:

- a. Provided by user and input through the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)) as the variable  $d$ . The last value to be entered is recorded as *displacement\_user* in the *Flux\_Notes* output table.
- b. If the user leaves the displacement height variable,  $d$ , as zero and the surface type is a crop or grass canopy, the displacement height is estimated in the program using equation 4.5 on page 138 in Rosenberg, et al. (1983):

$$d = 10^{0.979 \log_{10} h_c - 0.154} \quad (D-2a)$$

where  $h_c$  is canopy height that is measured periodically by the user throughout the growing season and entered into the program with the data logger keypad (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)). It should be set to a constant in the non-growing season.

For surface types other than crop, grass, or forest, the  $3/4$  rule, or  $d = 3h_c/4$ , is an alternative [p. 71 in Kaimal and Finnigan (1994)].

- c. If eddy-covariance variables are measured above a forest canopy, the  $2/3$  rule (page 116, Oke, 1987) will be used in the program as:

$$d = 2h_c / 3 \quad (D-2b)$$

In the program, whenever the canopy height and surface type are re-entered (see Section 4.2, *Enter Site-Specific Variables with Data Logger Keypad* (p. 12)), the zero displacement height is recalculated [Equations (D-2a) and (D-2b)] unless the user entered a specific value. Aerodynamic height (Equation D-2) is also recalculated. In the *Flux\_Notes* output table, the value for displacement height used during each averaging period is reported as  $d$ .

## D.6.2 Monin-Obukhov Length (L)

Monin-Obukhov length, as given by Rebmann et al. (2012) is an indication of surface layer depth, in which both shear and buoyancy drive the turbulent flows, generating turbulence kinetic energy. It is given by:

$$L = - \frac{u_*^3}{k \cdot (g_0 / \bar{T}_s) \cdot (\overline{w'T'_s})_{rf}} \quad (D-3)$$

where:  $k$  = von Karman constant (0.41)

$g_0$  = acceleration due to gravity at the sea level ( $9.81 \text{ m} \cdot \text{s}^{-2}$ )

$\bar{T}_s$  = sonic temperature (K)

$u_*$  – friction velocity ( $\text{m s}^{-1}$ ), given by [p. 67 in Stull (1988) and p. 384 in Wallace and Hobbs (2006)]:

$$u_* = \left( \left( \overline{u'w'} \right)_{rf}^2 + \left( \overline{v'w'} \right)_{rf}^2 \right)^{\frac{1}{4}} \quad (\text{D-4})$$

**NOTE**

Recalculation of the Monin-Obukhov length improves accuracy of the frequency correction factor.

The Monin-Obukhov length is used to determine the form of a cospectrum for a given covariance and as an independent variable in the cospectrum for stable conditions (see Appendix D.7, *Cospectra* (p. D-10), also see Kaimal 1972). During initial operation of the program and in each calculation interval (for example, 30 min), the Monin-Obukhov length must be preliminarily estimated using uncorrected friction velocity and buoyancy flux. Based on this preliminary Monin-Obukhov length, the appropriate cospectra function,  $C_{aw}(f)$ , [see Equation (D-1)] can be identified and used for the calculation of correction factors to preliminarily correct these three covariance variables :

$$\overline{u'w'}_r, \overline{v'w'}_r, \text{ and } \overline{w'T'}_r$$

Thereafter, the Monin-Obukhov length can be recalculated using these corrected covariance variables, which then requires the frequency correction factors to be recalculated, which can then be used to further correct the covariance values. This iterative calculation of Monin-Obukhov length, frequency correction factors, and covariance values is accomplished in the program using the While()... Wend() instructions and continues until the change in frequency correction factors is smaller than 0.0001 (Foken et al., 2012) or until 10 iterations have completed. The final Monin-Obukhov value is reported in the *Flux\_Notes* output table as  $L$ , and the number of iterations performed is reported as *iteration\_FreqFactor*.

**NOTE**

For stable conditions, only the initial calculation of Monin-Obukhov length is required; recalculation is not needed because Monin-Obukhov length is not used in the equations for cospectra under stable conditions and the sign of Monin-Obukhov does not change after recalculations of correction for covariance values used to calculate Monin-Obukhov length (see Appendix D.7, *Cospectra* (p. D-10)).

## D.7 Cospectra

This section contains mathematical descriptions of the cospectra functions used in Equation (D-1) for various covariance variables in different stabilities.

### D.7.1 Cospectra for $z/L > 0$ (stable surface layer)

For covariances  $\overline{u'w'}_r$  or  $\overline{v'w'}_r$  :

[from equation 21 in Moore (1986) and eq. 2.80 and Table 2.1 in van Dijk (2002b)]

$$fS_{uw}(f) = \frac{\frac{z}{\bar{u}} f}{A_{uw} + B_{uw} \left( \frac{z}{\bar{u}} f \right)^{2.1}} \quad (D-5)$$

$$A_{uw} = 0.124 \left( 1 + 7.9 \frac{z}{L} \right)^{0.75}$$

$$B_{uw} = 23.252 \left( 1 + 7.9 \frac{z}{L} \right)^{-0.825}$$

where  $\bar{u}$  is the total mean velocity, or the mean horizontal velocity after rotation about w-axis.

For covariances  $\overline{(T'_s w')_r}$ ,  $\overline{(T'_c w')_r}$ ,  $\overline{(T'_{FW} w')_r}$ ,  $\overline{(\rho'_{CO2} w')_r}$ , and  $\overline{(\rho'_{H2O} w')_r}$  :

[from equation 21 in Moore (1986), equations 12 and 13 in Moncrieff et al. (1997), and equation 2.80 and Table 2.1 in van Dijk (2002b)]

$$fS_{sw}(f) = \frac{\frac{z}{\bar{u}} f}{A_{sw} + B_{sw} \left( \frac{z}{\bar{u}} f \right)^{2.1}} \quad (D-6)$$

$$A_{sw} = 0.284 \left( 1 + 6.4 \frac{z}{L} \right)^{0.75}$$

$$B_{sw} = 9.3447 \left( 1 + 6.4 \frac{z}{L} \right)^{-0.825}$$

where subscript  $s$  is used to represent a scalar variable such as  $T_s$ ,  $T_c$ ,  $T_{fw}$ ,  $\rho_{co2}$ ,  $\rho_{co2\_LI}$ ,  $\rho_{h2o}$ ,  $\rho_{h2o\_kh}$ , or  $\rho_{h2o\_LI}$ .

## D.7.2 Cospectra for $z/L \leq 0$ (neutral to unstable)

For covariances  $\overline{(u' w')_r}$  or  $\overline{(v' w')_r}$  :

[from equation 21 in Moore (1986) and eq. 2.80 and Table 2.1 in van Dijk (2002b)]



$$fS_{uw}(f) = \begin{cases} \frac{20.78 \frac{z}{u} f}{\left(1 + 31 \frac{z}{u} f\right)^{1.575}} & \frac{z}{u} f < 0.24 \\ \frac{12.66 \frac{z}{u} f}{\left(1 + 9.6 \frac{z}{u} f\right)^{2.4}} & \frac{z}{u} f \geq 0.24 \end{cases} \quad (D-7)$$

For covariances  $\overline{(T'_s w')_r}$ ,  $\overline{(T'_c w')_r}$ ,  $\overline{(T'_{FW} w')_r}$ ,  $\overline{(\rho'_{CO2} w')_r}$ , and  $\overline{(\rho'_{H2O} w')_r}$ :

[from equation 25 in Moore (1986), equations 15 and 16 in Moncrieff. et al. (1997) and eq. 2.84 and Table 2.1 in van Dijk (2002b)]

Similar to stable conditions, the cospectrum of temperature with vertical velocity in neutral or unstable conditions presented below may be used as the cospectrum of other individual scalars with vertical velocity.

$$fS_{sw}(f) = \begin{cases} \frac{12.92 \frac{z}{u} f}{\left(1 + 26.7 \frac{z}{u} f\right)^{1.375}} & \frac{z}{u} f < 0.54 \\ \frac{4.378 \frac{z}{u} f}{\left(1 + 3.78 \frac{z}{u} f\right)^{2.4}} & \frac{z}{u} f \geq 0.54 \end{cases} \quad (D-8)$$

## D.8 Sub-Transfer Functions

The total transfer function found in Equation (D-1) consists of the products of all sub-transfer functions of each variable used to calculate a covariance. Sub-transfer functions account for block averaging, line averaging, sensor volume averaging (negligible in the cases of the IRGASON and EC150), electronic data filtering, sensor time response (for example, air temperature measured using FW sensors), and sensor separation (for example, the  $x$  and  $y$  separations of CSAT3A and EC150). These sub-transfer functions are described in the following sections.

### D.8.1 Finite Time Block Averaging

The sub-transfer function for finite time block averaging is derived from equation 4 in Kaimal et al. (1989) and equation 3 in Massman (2000).

Every covariance is an average covariance over a finite block of time as defined by the user (e.g., 30 or 60 minutes). Having a finite time block leads to

attenuation of low frequencies, and therefore, all covariance variables require a sub-transfer function to account for this. The sub-transfer function  $[T_{sw\_BA}(f, T_{ba})]$  due to a finite block averaging period ( $T_{ba}$ ) is given by:

$$T_{sw\_BA}(f, T_{ba}) = 1 - \frac{\sin^2(\pi T_{ba} f)}{(\pi T_{ba} f)^2} \quad (D-9)$$

where subscript *BA* or *ba* indicates **block averaging** and  $T_{ba}=1800$  seconds if a period of 30 minutes is used.

## D.8.2 Line Averaging

### Sub-transfer functions for variances of individual variables

The attenuation of variance of vertical velocity (*w*) from line average is described using equation 9 in Moore (1986), page 610 in Moncrieff (1997), and equation 4.10 in Foken et al (2012).

The resulting sub-transfer function applied to vertical wind variance  $[T_{ww\_LA}(f, l_{pt\_csat}, \bar{u})]$  is as follows:

$$T_{ww\_LA}(f, l_{pt\_csat}, \bar{u}) = \frac{4}{(2\pi l_{pt\_csat} / \bar{u}) f} \left( 1 + \frac{\exp(-\frac{2\pi l_{pt\_csat}}{\bar{u}} f)}{2} - \frac{1.5 \left[ 1 - \exp(-\frac{2\pi l_{pt\_csat}}{\bar{u}} f) \right]}{(2\pi l_{pt\_csat} / \bar{u}) f} \right) \quad (D-10)$$

The sub-transfer function for horizontal velocity variance  $[T_{uu\_LA}(f, l_{pt\_csat}, \bar{u})]$  has not been well defined for sonic anemometry [page 22 in Moore (1986) and page 46 in van Dijk (2002b)]. Therefore, the sub-transfer function used by van Dijk (2002b) for horizontal wind is adopted as an approximation [eq. 2.70 in van Dijk (2002b)]:

$$T_{uu\_LA}(f, l_{pt\_csat}, \bar{u}) = \left[ \frac{\sin\left(\frac{\pi l_{pt\_csat}}{\bar{u}} f\right)}{\frac{\pi l_{pt\_csat}}{\bar{u}} f} \right]^2 \quad (D-11)$$

For the variance of a scalar, *s*, measured by a gas analyzer, the sub-transfer function,  $T_{ss\_LA}(f, l_{pt\_irga}, \bar{u})$ , is given as follows [eq. 7 in Moore (1986) and eq. 2.68 in van Dijk (2002b), eq. 4.12 in Foken et al (2012)]:

$$T_{ss\_LA}(f, l_{pt\_irga}, \bar{u}) = \frac{1}{\frac{2\pi l_{pt\_irga}}{\bar{u}} f} \left( 3 + \exp(-\frac{2\pi l_{pt\_irga}}{\bar{u}} f) - \frac{4 \left[ 1 - \exp(-\frac{2\pi l_{pt\_irga}}{\bar{u}} f) \right]}{\frac{2\pi l_{pt\_irga}}{\bar{u}} f} \right) \quad (D-12)$$

**Sub-transfer functions for covariance due to line averaging**

Sub-transfer functions for covariance of certain scalars with vertical wind are given below:

$$\overline{u'w'} \text{ or } \overline{v'w'}$$

$$T_{uw\_LA}(f, l_{pt\_csat}, \bar{u}) = \sqrt{T_{uu\_LA}(f, l_{pt\_csat}, \bar{u}) T_{ww\_LA}(f, l_{pt\_csat}, \bar{u})} \quad (D-13)$$

$$\overline{s'w'} \text{ (where } s \text{ is a variable from the IRGA)}$$

$$T_{sw\_LA}(f, l_{pt\_IRGA}, l_{pt\_csat}, \bar{u}) = \sqrt{T_{ss\_LA}(f, l_{pt\_IRGA}, \bar{u}) T_{ww\_LA}(f, l_{pt\_csat}, \bar{u})} \quad (D-14)$$

$$\overline{T'_s w'} \text{ (from equations 5 to 8 in van Dijk, 2002a)}$$

In cylindrical coordinates, the sub-transfer function for line averaging of buoyancy flux measured using Campbell sonic anemometer is as follows:

$$T_{T_s w\_LA}(f, l_{pt\_csat}, \bar{u}) = \frac{91}{180\pi k^2} \int_0^\infty \int_0^{2\pi} K \sqrt{k^2 + K^2} \frac{k^2 + K^2 \sin^2 \theta}{k^2 + K^2} \sum_{i=1}^3 \sin c \frac{\mathbf{k} \cdot \mathbf{l}_i}{2} d\theta dK \quad (D-15)$$

where  $k$  is the wave number in the streamwise direction given by

$$k = \frac{2\pi f}{\bar{u}} \quad (D-16)$$

and where  $k$  is the wave number vector in cylindrical coordinates given by:

$$\mathbf{k} = [k \quad K \sin \theta \quad K \cos \theta] \quad (D-17)$$

and where  $\mathbf{l}_i$  ( $i = 1, 2, \text{ or } 3$ ) is a path vector that expresses a path length as three components in three dimensions, given by:

$$\mathbf{l}_1 = l_{pt\_csat} \begin{bmatrix} -\sin 30^\circ \\ 0 \\ \cos 30^\circ \end{bmatrix}, \mathbf{l}_2 = \frac{l_{pt\_csat}}{2} \begin{bmatrix} \sin 30^\circ \\ \sqrt{3} \sin 30^\circ \\ 2 \cos 30^\circ \end{bmatrix}, \text{ and } \mathbf{l}_3 = \frac{l_{pt\_csat}}{2} \begin{bmatrix} \sin 30^\circ \\ -\sqrt{3} \sin 30^\circ \\ 2 \cos 30^\circ \end{bmatrix} \quad (D-18)$$

The integration of equation (D-15) requires much computation, so its numerical form in Table 1 of van Dijk (2002a) is used (see TABLE D-1).

**TABLE D-1. Numerical form (transfer function values versus normalize frequencies) of sub-transfer function of buoyancy flux measured by a CSAT3**

Normalized Frequency	< 0.01	0.1	0.2	0.5	1.0	1.2	1.4	1.6
Sub-transfer function values	1.0000	0.9992	0.9976	0.9900	0.9670	0.9550	0.9417	0.9274
Normalized frequency	1.8	2.0	2.2	2.4	2.6	2.8	3.0	4.0
Sub-transfer function values	0.9122	0.8962	0.8797	0.8626	0.8452	0.8274	0.8096	0.7201
Normalized frequency	5.0	6.0	7.0	8.0	9.0	10.0	14.0	20.0
Sub-transfer function values	0.6353	0.5588	0.4922	0.4355	0.3879	0.3481	0.2445	0.1700
Normalized frequency	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100.0
Sub-transfer function values	0.1134	0.08503	0.06802	0.05668	0.04859	0.04251	0.03779	0.03401

For normalized frequencies between the values listed in the table, the sub-transfer function is linearly interpolated between two neighboring independent normalized frequencies. For normalized frequencies less than or equal to 0.01 Hz, the transfer function value is set to 1. For normalized frequencies greater than 100 Hz, trends from the first and second order numerical derivatives show that this sub-transfer function becomes nearly constant beyond 300 Hz at a value of  $1.155511 \times 10^{-4}$ . Therefore, for normalized frequencies from 300 Hz to 10,000 Hz, the sub-transfer function is set to this value, and for frequencies falling between 100 Hz and 300 Hz, the sub-transfer function is estimated by linear interpolation.

### D.8.3 Volume Averaging

Volume averaging is considered negligible in the cases of an IRGASON and EC150 due to the very small diameter to path length ratio, however the sub-transfer function for volume averaging is briefly described here for completeness. A sensor such as a krypton hygrometer (KH20) has a much higher diameter-path length ratio, so the volume averaging must be taken into account. Its optical beam diameter is 8 mm, and its path length is 12 to 15 mm (see the calibration document for the unique path length for a particular KH20). Andreas (1981) derived an exact transfer function for volume averaging [equation (18) in Andreas (1981)]. This transfer function includes a first-order Bessel function of the first kind, which makes the integration of the sub-transfer function over the frequency domain in need of significant computation time.

Later, Moene (2003) used a simpler function to approximate equation (18) of Andreas (1981) for Krypton hygrometers. His approximation was developed using the transfer function of Andreas (1981) for a diameter-length ratio between 0.5 and 1.0 when the ratio of the Kolmogorov microscale (1 mm in atmosphere) to the path length is 0.1 [Fig. 2 in Andreas (1981)]. The approximation equation [see page 650 in Moene (2003)] is given by:

$$T_{h2o\_KH\_VA}(f, p_{KH}, \bar{u}) = \exp \left[ -2 \left( \frac{p_{KH}}{\bar{u}} f \right)^2 \right] \quad (D-19)$$

where  $p_{KH}$  is the path length of KH20.

## D.8.4 FIR Filtering

The sub-transfer function for the various data filters available on the EC100 electronics (the EC100 is the electronics module used with the EC150, CSAT3A, and IRGASON) has not been developed yet. However, it is assumed to be negligible compared to other sub-transfer functions, assuming the bandwidth has been appropriately selected for flux measurements.

## D.8.5 Time Constant

If a fine wire thermocouple is used, a sub-transfer function describing the frequency response of the thermocouple should be used and is described by a simple first order gain function [Square of equation 2 in Moore (1986)]:

$$T_{TT\_TC}(f, \tau_{FW}) = \frac{1}{1 + (2\pi\tau_{FW}f)^2} \quad (D-20)$$

where:  $\tau_{FW}$  is the time constant of the FW.

The value of  $\tau_{FW}$  depends on the physical properties of air, physical properties of the thermocouple, the diameter of the thermocouple wire ( $D$ , entered by a user), and the Nusselt number (Nu). It is given by [equation 3 in Moore (1986) and equation 4 in Shapland et al. (2014)]:

$$\tau_{FW} = \gamma \frac{\rho_{FW} C_{FW}}{k_a \text{Nu}} D^2 \quad (D-21)$$

where:  $\gamma$  is the shape coefficient. It is 0.25 for cylindrical and 0.167 for spherical sensors. For a FW, a cylindrical shape is assumed since heat can be conducted through two paths around the junction, each having a cylindrical shape.

$\rho_{FW}$  is the material density of the thermocouple  
 $\{[8920(\text{constantan}) + 8730(\text{chromel})]/2 = 8825 \text{ kg/m}^3$ ,  
 Omega product literature (undated)}

$C_{FW}$  is the specific heat of the thermocouple materials  
 $\{[0.094(\text{constantan}) + 0.107(\text{chromel})]/2 = 0.1005 \text{ cal/(g } ^\circ\text{C)} = 420.7734 \text{ J/(kg } ^\circ\text{C)}$ , Omega product literature  
 (undated)}

$k_a$  is the thermal conductivity of air  $[7.038086 \times 10^{-5} T + 2.42507 \times 10^{-2} \text{ in W/(m } ^\circ\text{C)}$ , where  $T$  is air temperature in  $^\circ\text{C}$ , Table 1 in Montgomery (1947)]

**Nu** is the Nusselt number. The Nusselt number for a sphere is used because the aerodynamics around the junction are influenced by its 3D dimensions [equation 4 in Moore (1986)]. It is calculated as follows:

$$\mathbf{Nu} = 2.00 + 0.18\mathbf{Re}^{0.67} \quad (\text{D-22})$$

where **Re** is Reynolds' number [equation 3.1-2 in Geankoplis (1993)]

$$\mathbf{Re} = \frac{2\rho_a D\bar{u}}{\mu} \quad (\text{D-23})$$

where:  $\rho_a$  is air density (calculated online by the data logger),

$\bar{u}$  is horizontal wind speed (use sonic data),

$\mu$  is viscosity of air [ $4.9821 \times 10^{-8}T + 1.7168 \times 10^{-5}$  in  $\text{kg}/(\text{m}\cdot\text{s})$ , see Table 1 in Montgomery (1947)]

## D.8.6 Spatial Separation

For eddy covariance measurements that use two spatially separated sensors for measurements of wind velocity and a scalar, a passing eddy may be measured by the two sensors at different times if the sensors are mounted along the mean wind direction, creating a time lag in the measurements of the downstream sensor relative to the upstream one. Alternatively, it is possible that the eddy will be measured by only one of the two sensors if the sensors are mounted with a separation perpendicular to the mean wind direction (for example, a lateral separation with sensors mounted in a crosswind orientation) and the eddy is smaller than the separation distance. This can also happen if the boundary of the eddy passing through one sensor's measurement volume does not reach the measurement volume of the other sensor. Accordingly, the separation along the wind direction is defined as lag distance and the separation in crosswind direction as lateral distance.

The magnitude of covariance is decreased due to both the lag distance and the lateral distance (Horst and Lenschow 2009). In data processing, the loss of covariance due to the lag distance may be significantly or largely recovered by realigning the data with various time lags in order to maximize the covariance (such as, lag maximization), and the loss of covariance due to lateral distance may be recovered using a frequency correction (Foken et al. 2012). For both of these corrections, the physical lag and lateral distances are needed.

In the installation of sensors, the horizontal coordinates of the center of the measurement volume of the scalar sensor relative to the sonic coordinate system (see FIGURE D-1) should be recorded. The coordinates can be expressed as a separation vector  $[x, y]$ .

When wind comes from a direction of zero degrees (i.e., against the direction in which the sonic anemometer points), the  $x$  component of the vector is the lag distance and the  $y$  component of the vector is lateral distance. When the wind direction is not zero degrees, the separation vector may be projected onto the wind and crosswind axes by knowing the wind direction ( $\theta_w$ ) relative to the

sonic coordinate system and using a coordinate rotation. The resulting projection along the wind direction is lag distance ( $d_{lag}$ ) and the projection in crosswind direction is lateral distance ( $d_{lat}$ ).

These are given by:

$$\begin{bmatrix} d_{lag} \\ d_{lat} \end{bmatrix} = \begin{bmatrix} \cos \theta_w & \sin \theta_w \\ -\sin \theta_w & \cos \theta_w \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \quad (D-24)$$

The lag distance ( $d_{lag}$ ) along with wind speed will be used by the data logger for lag maximization by applying an appropriate lag to the measurement scans to align the sensors (see lag maximization). The lateral distance is used in a sub-transfer function of frequency response due to sensor separation,  $T_{sw\_SP}(f, d_{lat}, \bar{u})$ , which is given as follows [equation 4.8 in Foken, et. al. (2012)]:

$$T_{sw\_SP}(f, d_{lat}, \bar{u}) = \exp \left[ -9.9 \left( \frac{f d_{lat}}{\bar{u}} \right)^{1.5} \right] \quad (D-25)$$

## D.8.7 Total Transfer Function

A composite or total transfer function is given by the product of the appropriate sub-transfer functions for a particular covariance. The total transfer functions used by the data logger are given in this section (FIR correction currently not included).

For  $\overline{u'w'}$  or  $\overline{v'w'}$  :

$$T_{uw}(f, l_{pt\_csat}, T_{ba}, \bar{u}) = T_{uw\_BA}(f, T_{ba}) T_{uw\_LA}(f, l_{pt\_csat}, \bar{u}) \quad (D-26)$$

For  $\overline{T'_s w'}$  :

$$T_{T_s w}(f, l_{pt\_csat}, T_b, \bar{u}) = T_{T_s w\_BA}(f, T_{ba}) T_{T_s w\_LA}(f, l_{pt\_csat}, \bar{u}) \quad (D-27)$$

For  $\overline{S'w'}$  (where s is a variable measured by the IRGA) :

$$T_{sw}(f, l_{pt\_csat}, l_{pt\_IRGA}, d_{lat}, T_{ba}, \bar{u}) = T_{sw\_BA}(f, T_{ba}) T_{sw\_LA}(f, l_{pt\_csat}, l_{pt\_IRGA}, \bar{u}) T_{sw\_SP}(f, d_{lat}, \bar{u}) \quad (D-28)$$

For  $\overline{T'_{FW} w'}$  :

$$T_{T_{FW} w}(f, l_{pt\_csat}, d_{lat}, \tau_{FW}, T_{ba}, \bar{u}) = T_{T_{FW} w\_BA}(f, T_{ba}) \sqrt{T_{ww\_LA}(f, l_{pt\_csat}, \bar{u}) T_{TT\_TC}(f, \tau_{FW})} T_{sw\_SP}(f, d_{lat}, \bar{u}) \quad (D-29)$$

## D.9 Working Model

Evaluating the correction factor in Equation (D-1) in the data logger program requires numerical integration. Because the cospectrum changes exponentially faster at low frequencies than at high frequencies, the interval of integration can be exponentially increased throughout the integration in order to save computation time without significantly reducing accuracy. Accordingly,  $\ln f$  is used as an integration variable that increases at equal logarithmic intervals of frequency ( $f$ ), which effectively increments the frequency interval exponentially for fast integration over the integration domain. This results in a working formula that is used to find the covariance:

$$\overline{(\alpha' w')}_{rf} = \left( \overline{\alpha' w'} \right)_r \left\{ \frac{\int_0^\infty [f S_{\alpha w}(f)] d(\ln f)}{\int_0^\infty T_{\alpha w}(f) [f S_{\alpha w}(f)] d(\ln f)} \right\} \quad (D-30)$$

Recall that even though simple notation for  $T_{\alpha w}(f)$  has been used, this is an overall transfer function that is comprised of the sub-transfer functions presented in the sections above and includes independent variables such as wind speed ( $\bar{u}$ ), block average period, measurement path length, and/or sensor time constant and/or lateral separation distance. Accordingly, the components of the combined transfer function for different variables of vectors and scalars are unique due to sensor specifications and measurement installations.

## D.10 Programmatic Approach to Computations for Correction Factors

The correction factor in model (D-30) has a numerator and a denominator. Its numerator is found from a normalized spectrum, and its denominator is determined by numerical integration. For both normalized and non-normalized cospectra, we numerically integrate both the numerator and denominator. Moore (1986) used the Composite Simpson's rule to estimate this denominator. In his estimation, 19 equal integration intervals at a scale of natural logarithm from  $10^{-5}$  to 5 Hz were used, which resulted in an integration error smaller than 1%. Currently, this can be further improved due to faster computational speeds in Campbell data loggers compared to microcomputers at that time. By increasing the integration range and decreasing the integration intervals, the data logger can more accurately account for frequency attenuation, particularly in the lower frequencies of the block averaging sub-transfer function. Specifically, we extend the integration range from  $10^{-6}$  to  $10^4$  Hz and divide the range into 100 frequency bins. It is believed that the integration error should be significantly smaller than Moore (1986) and the accuracy sufficient.



Because the cospectrum may change exponentially and dramatically in lower frequencies, the logarithm scale of cyclic frequency may be used for a numerical integration interval (bin width). For 100 bins from  $10^{-6}$  to  $10^4$  Hz, the base frequency interval ( $\Delta f$ ) is 1.258925 since  $10^{-6} \times 1.258925^{100} = 10000$ . The lower frequency boundary of the  $j$ th interval is indexed as the  $(j-1)$ th frequency and the right boundary frequency is indexed as the  $j$ th frequency. The interval of integration (bin width) at natural logarithm scale  $[\Delta \ln(f)]$  is given by:

$$\begin{aligned} \Delta \ln(f) &= \ln(10^{-6} \Delta f^j) - \ln(10^{-6} \times \Delta f^{j-1}) \\ &= \ln \frac{10^{-6} \Delta f^j}{10^{-6} \Delta f^{j-1}} = \ln \Delta f \end{aligned} \quad (\text{D-31})$$

The Composite Simpson's rule writes the integration for the numerator in model (8.1) as (page 186 in Burden and Faires (1993):

$$\begin{aligned} \int_0^\infty [f S_{\alpha w}(f)] d(\ln f) &\approx \int_{10^{-6}}^{10000} [f S_{\alpha w}(f)] d(\ln f) \\ &= \frac{\ln(\Delta f)}{3} \left\{ \left[ 10^{-6} S_{\alpha w}(10^{-6}) \right] + 4 \sum_{k=1}^{50} \left[ 10^{-6} \Delta f^{2k-1} S_{\alpha w}(10^{-6} \Delta f^{2k-1}) \right] \right. \\ &\quad \left. + 2 \sum_{k=1}^{49} \left[ 10^{-6} \Delta f^{2k} S_{\alpha w}(10^{-6} \Delta f^{2k}) \right] + \left[ 10^4 S_{\alpha w}(10^4) \right] \right\} \end{aligned} \quad (\text{D-32})$$

with an error term as describe on page 186 (Burden and Fares (1993):

$$\begin{aligned} \text{Error} &= \frac{10^4 - 10^{-6}}{180} \times (\ln \Delta f)^4 \frac{2}{100} \sum_{j=1}^{50} \left[ \xi_j S_{\alpha w}(\xi_j) \right]^{(4)} \\ &\approx \frac{20}{18} \times (\ln \Delta f)^4 \sum_{j=1}^{50} \left[ \xi_j S_{\alpha w}(\xi_j) \right]^{(4)} \end{aligned} \quad (\text{D-33})$$

where  $\xi$  is a value of frequency that can maximize the value in the square bracket. The evaluation of this term requires more complicated calculations because the 4th order derivative of the integrated function is needed. We do not evaluate this term now, but equation (D-33) can show how the error can be reduced by adding the number of integration intervals and narrowing the width of the interval.

Similarly, the denominator with Simpson's rule applied becomes:

$$\begin{aligned} \int_0^\infty T_{\alpha w}(f) [f S_{\alpha w}(f)] d(\ln f) &\approx \int_{10^{-6}}^{10000} T_{\alpha w}(f) [f S_{\alpha w}(f)] d(\ln f) \\ &= \frac{\ln(\Delta f)}{3} \left\{ \left[ T_{\alpha w}(10^{-6}) 10^{-6} S_{\alpha w}(10^{-6}) \right] + 4 \sum_{k=1}^{50} T_{\alpha w}(10^{-6} \Delta f^{2k-1}) \left[ 10^{-6} \Delta f^{2k-1} S_{\alpha w}(10^{-6} \Delta f^{2k-1}) \right] \right. \\ &\quad \left. + 2 \sum_{k=1}^{49} T_{\alpha w}(10^{-6} \Delta f^{2k}) \left[ 10^{-6} \Delta f^{2k} S_{\alpha w}(10^{-6} \Delta f^{2k}) \right] + T_{\alpha w}(10^4) \left[ 10^4 S_{\alpha w}(10^4) \right] \right\} \end{aligned} \quad (\text{D-34})$$

The error term of this numerical integration can be calculated using equation (D-33) if the term  $\xi_j S_{\text{cov}}(\xi_j)$  is replaced with  $T_{\text{cov}}[\xi_j] \xi_j S_{\text{cov}}(\xi_j)$ .

The code in the program used to calculate the correction factor of one covariance (*Cor\_factor*) is outlined below:

*Cor\_factor* = 0

for  $j = 0$  to 100 (100 steps)

$f = 10^{-6} \times 1.258925^j$  (Calculation of frequency)

$m = 2 + 4 \times (j \text{ MOD } 2) - \text{ABS}(j = 0) - \text{ABS}(j = 100)$

**NOTE**

$M = 1$  for  $j = 0$  and  $j = 100$ . For all other  $j$ ,  $m = 4$  if  $j$  is odd and  $m = 2$  if  $j$  is even).

Numerator = Numerator +  $m \times [f S_{\alpha\beta}(f)]$

Denominator = Denominator +  $m \times T_{\alpha\beta}(f) [f S_{\alpha\beta}(f)]$

Next  $j$

*Cor\_factor* = Numerator/Denominator

## D.11 References

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# Appendix E. WPL Corrections

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Due to the vertical gradient of air temperature in the atmospheric surface layer, rising air parcels have different temperatures and densities than descending ones. For example, in the case of upward (positive) heat flux when the air closest to the ground is warmest, rising air parcels on average will be warmer and less dense than descending ones. In this same case, suppose that the CO<sub>2</sub> or H<sub>2</sub>O fluxes are zero (rising and descending parcels carry the same amount of CO<sub>2</sub> and H<sub>2</sub>O), the measurements from an open-path eddy covariance (EC) system will still report negative (downward) fluxes simply because of the correlation between rising air parcels and lower air density. This is explained by mass conservation or air continuity; the decrease in air density due to the increase in air temperature while the total pressure in surface layer changes very little, forces air to expand upwards in the atmospheric surface layer. This expansion generates an upward (positive) flux of air at the measurement point and leads to a slightly positive mean vertical velocity. Thus, the downward CO<sub>2</sub> or H<sub>2</sub>O flux measured by open-path EC system may be explained by the upward flux of air from a net upward vertical velocity.

Depending on whether the temperature profile increases or decreases with height, the mean vertical velocity may be negative or positive. Typically, it ranges from  $-0.75$  to  $1.5$  mm/s when sensible heat flux is between  $-200$  and  $600$  W/m<sup>2</sup> (Fig.1 in Webb et al. [1980]). This change in vertical velocity due to change in air density is too small to be measured by a 3D sonic anemometer with sufficient accuracy.

Since typical applications of the open-path EC method do not account for fluxes associated with non-zero mean flows ( $\overline{w} \neq 0$ ), an appropriate correction for the vertical velocity due to heat and water vapor transfer is needed.

## E.1 Basic Considerations

Air density ( $\rho_a$ ) is a sum of partial densities: dry air density ( $\rho_d$ ), water vapor density ( $\rho_v$ ), and CO<sub>2</sub> density ( $\rho_{co2}$ ), given by:

$$\rho_a = \rho_d + \rho_v + \rho_{co2} \quad (\text{E-1})$$

The contribution of  $\rho_{CO2}$  relative to  $\rho_d$  and  $\rho_v$  vapor is very small, and thus can be considered negligible to the total air density. The equation therefore becomes:

$$\rho_a = \rho_d + \rho_v \quad (\text{E-2})$$

The individual gas laws give the partial pressures of dry air ( $p_d$ ), water vapor ( $p_v$ ), and ( $p_{co2}$ ) as follows:

$$\begin{aligned}
 p_d &= \frac{R^*}{m_d} \rho_d T \\
 p_v &= \frac{R^*}{m_v} \rho_v T \\
 p_{CO_2} &= \frac{R^*}{m_{CO_2}} \rho_{CO_2} T
 \end{aligned} \tag{E-3}$$

where subscripts  $d$ ,  $v$ , and  $CO_2$  denote dry air, water vapor, and carbon dioxide, respectively, and are used throughout;  $m$  is molecular mass;  $R^*$  is the universal gas constant ( $8.3143 \text{ J K}^{-1} \text{ mol}^{-1}$ , page 467 of Wallace and Hobbs [2006]), and  $T$  is absolute temperature.

The total air pressure ( $p_a$ ) is given by:

$$p_a = p_d + p_v + p_{CO_2} \tag{E-4}$$

The air pressure, dry-air density, water-vapor density, and  $CO_2$  density are measured and calculated in an EC system. Although the partial pressures of the different gas components are normally not measured, the other measured variables may be used to derive the partial pressures. Submitting equation (E-3) into equation (E-4) yields:

$$\frac{p_a}{R^* T} = \frac{\rho_d}{m_d} + \frac{\rho_v}{m_v} + \frac{\rho_{CO_2}}{m_{CO_2}} \approx \frac{\rho_d}{m_d} + \frac{\rho_v}{m_v} \tag{E-5}$$

Equation (E-5) describes the basic relationship of air and water vapor densities to temperature and atmospheric pressure. If the term

$$\frac{1}{T} = \frac{1}{(\bar{T} + T')} = \frac{1}{\bar{T} \left( 1 + \frac{T'}{\bar{T}} \right)} \tag{E-6}$$

is expended in a power series of  $T' / \bar{T}$ , the partial densities in equation (E-5) can be written in forms of instantaneous, mean, and fluctuation variables as follows:

$$\left\{ \frac{\rho_d}{m_d} + \frac{\rho_v}{m_v} = \frac{p_a}{R^* \bar{T}} \left\{ 1 - \frac{T'}{\bar{T}} + \left( \frac{T'}{\bar{T}} \right)^2 - \left( \frac{T'}{\bar{T}} \right)^3 + \dots \right\} \right. \tag{E7a}$$

$$\left\{ \frac{\bar{\rho}_d}{m_d} + \frac{\bar{\rho}_v}{m_v} = \frac{p_a}{R^* \bar{T}} \left\{ 1 + \frac{\overline{T'^2}}{\bar{T}^2} - \frac{\overline{T'^3}}{\bar{T}^3} + \dots \right\} \right. \tag{E7b} \quad (\text{E-7})$$

$$\left\{ \frac{\rho'_d}{m_d} + \frac{\rho'_v}{m_v} = \frac{p_a}{R^* \bar{T}} \left\{ -\frac{T'}{\bar{T}} + \frac{T'^2 - \overline{T'^2}}{\bar{T}^2} - \frac{T'^3 - \overline{T'^3}}{\bar{T}^3} + \dots \right\} \right. \tag{E7c}$$

Equation (E7b) can further be expressed as:

$$\frac{p_a}{R^* \bar{T}} = \left( \frac{\bar{\rho}_d}{m_d} + \frac{\bar{\rho}_v}{m_v} \right) \left\{ 1 + \frac{\bar{T}'^2}{\bar{T}^2} - \frac{\bar{T}'^3}{\bar{T}^3} + \dots \right\}^{-1} \quad (\text{E-8})$$

Substituting equation (E-8) into equation (E7c) yields:

$$\frac{\rho'_d}{m_d} + \frac{\rho'_v}{m_v} = \left( \frac{\bar{\rho}_d}{m_d} + \frac{\bar{\rho}_v}{m_v} \right) \left\{ -\frac{T'}{\bar{T}} + \frac{T'^2 - \bar{T}^2}{\bar{T}^2} - \frac{T'^3 - \bar{T}^3}{\bar{T}^3} + \dots \right\} \left\{ 1 + \frac{\bar{T}'^2}{\bar{T}^2} - \frac{\bar{T}'^3}{\bar{T}^3} + \dots \right\}^{-1} \quad (\text{E-9})$$

By dropping the second order term ( $< 10^{-4}$ ) of absolute temperature, the fluctuation of dry air density can be expressed as:

$$\begin{aligned} \rho'_d &= -\frac{m_d}{m_v} \rho'_v - \bar{\rho}_d \left( 1 + \frac{m_d}{m_v} \frac{\bar{\rho}_v}{\bar{\rho}_d} \right) \frac{T'}{\bar{T}} \\ &= -\mu \rho'_v - \bar{\rho}_d (1 + \mu \sigma) \frac{T'}{\bar{T}} \end{aligned} \quad (\text{E-10})$$

where  $\mu$  is the molecular weight ratio of dry air to water vapor, and  $\sigma$  is the mean water vapor mixing ratio.

## E.2 Governing Constraint and Mean Vertical Velocity

The governing constraint that the mean vertical flux of dry air constituent should be zero is given by:

$$\overline{w \rho_d} = 0 \quad (\text{E-11})$$

Equation (E-11) is equivalent to:

$$\overline{w \rho_d} = (\bar{w} + \overline{w'}) (\bar{\rho}_d + \overline{\rho'_d}) = \bar{w} \bar{\rho}_d + \bar{w} \overline{\rho'_d} + \overline{w' \bar{\rho}_d} + \overline{w' \rho'_d} = \bar{w} \bar{\rho}_d + \overline{w' \rho'_d} \quad (\text{E-12})$$

Equations (E-11) and (E-12) give:

$$\bar{w} = -\frac{\overline{w' \rho'_d}}{\bar{\rho}_d} \quad (\text{E-13})$$

Submitting equation (E-10) into this equation yields:

$$\bar{w} = \mu \frac{\overline{w' \rho'_v}}{\bar{\rho}_d} + (1 + \mu \sigma) \frac{\overline{w' T'}}{\bar{T}} \quad (\text{E-14})$$

## E.3 Eddy Covariance Measurements

### E.3.1 CO<sub>2</sub>

The flux of CO<sub>2</sub> can be written as:

$$F_{CO_2} = \overline{w\rho_{CO_2}} = \overline{w'\rho'_{CO_2}} + \bar{w}\bar{\rho}_{CO_2} \quad (E-15)$$

Replacing the mean vertical velocity ( $\bar{W}$ ) in the equation with equation (E-14) yields:

$$F_{CO_2} = \overline{w'\rho'_{CO_2}} + \left[ \mu \frac{\bar{\rho}_{CO_2}}{\bar{\rho}_d} \overline{w'\rho'_v} + (1 + \mu\sigma) \frac{\bar{\rho}_{CO_2}}{\bar{T}} \overline{w'T'} \right] \quad (E-16)$$

The term in the rectangle bracket is the WPL correction. The first term is due to water flux and the second is due to heat flux.

$\bar{\rho}_{CO_2}$  is the mean CO<sub>2</sub> density measured by an IRGA

$\bar{\rho}_d$  is the mean dry air density calculated from air temperature, pressure, and water vapor density

$\bar{T}$  is the mean air temperature in Kelvin

$\mu$  is 1.60802 (the ratio of dry air molecular weight [ $m_d = 28.97 \text{ kg}\cdot\text{kmol}^{-1}$ ] to water molecular weight [ $m_v = 18.016 \text{ kg}\cdot\text{kmol}^{-1}$ ], page 466 in Wallace and Hobbs [2006])

$\sigma$  is the mean water vapor mixing ratio [ratio of mean water vapor density ( $\bar{\rho}_v$ ) to mean dry air density ( $\bar{\rho}_d$ ).

$\overline{w'\rho'_v}$  is the water vapor flux measured using a sonic anemometer and IRGA.

$\overline{w'T'}$  is the heat flux (after rotations, frequency, and SND corrections) calculated from a sonic anemometer and optionally with a fine-wire thermocouple.

### E.3.2 H<sub>2</sub>O

The flux of water vapor is written as:

$$E = \overline{w\rho_v} = \overline{w'\rho'_v} + \bar{w}\bar{\rho}_v \quad (E-17)$$

Replacing the mean vertical velocity ( $\bar{W}$ ) in the equation with equation (E-14) yields:

$$E = \overline{w'\rho'_v} + \left[ \mu\sigma \overline{w'\rho'_v} + (1 + \mu\sigma) \frac{\bar{\rho}_v}{\bar{T}} \overline{w'T'} \right] \quad (E-18)$$



The term in the rectangle bracket is the WPL correction term. The first term is due to water flux itself and the second is due to heat flux.

$\overline{\rho_v}$  is the mean water vapor density measured by IRGA

$\overline{w'\rho_v'}$  is the water vapor flux (after rotation and frequency corrections) measured using sonic anemometer and IRGA.

## E.4 References

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# Appendix F. Data Quality Grading

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Data quality assurance (QA) and quality control (QC) are recommended for eddy covariance (EC) measurements because of complex calculation procedures (Foken et al. 2012). A number of publications on QA and QC for EC measurements are available (for example, Foken and Wichura 1996, Vickers and Mahurt 1997, Shearman 1992, Moncrieff et al. 1997, Aubinet et al. 2000, Foken et al 2004, 2012).

In the case of this data logger program, QA is accomplished using diagnostic outputs from the measurement system's sonic anemometer and infrared gas analyzer. Specifically, the data logger only uses raw data for flux calculations when the diagnostic values from both sensors are zero (i.e., sensors work normally and measurements are in their reasonable ranges), when the measurements are within the calibrated range of the sensors, and when the signal strengths are adequate (i.e., when nothing is blocking the optical path). Even when raw data are not used for flux calculations, they are still stored in the time series data table. More details on diagnostics are found in the manual of the respective sensor. Regarding QC, the data logger program follows the method presented in Foken et al. (2012) to grade the relative quality of CO<sub>2</sub>, latent heat, sensible heat, and momentum fluxes. Specifically, the following three variables are calculated and used to grade the quality of the data:

- **Relative Non-stationarity** ( $RN_{cov}$ ) to describe the steady state
- **relative Integral Turbulence Characteristics** ( $ITC$ ) to define the developed turbulence condition
- **horizontal wind angle** in the sonic anemometer coordinate system

Sections F.1 through F.3 give more information on each of these variables and how a quality grade for each is assigned. Section F.4 describes how an overall quality grade is found, and Section F.5 describes how this is implemented into the data logger program.

## NOTE

Due to differences in sonic anemometer models and geometries used in the AmeriFlux network, AmeriFlux prescribes the usage of only the steady-state and integral turbulence characteristics tests as presented in Foken et al. (2004) for its standard QC results. Accordingly, the QC outputs in the *Flux\_AmeriFluxFormat* output table (e.g., FC\_SSITC\_TEST) ignore the wind direction and apply the tests as presented in the paper.

See <http://ameriflux.lbl.gov/data/aboutdata/data-variables/>.

## F.1 Relative Non-stationarity ( $RN_{cov}$ ) for Steady State

Turbulence flux measurement theory is valid under the steady state conditions of turbulent flows. In such conditions, the surface layer turbulent flow structure is independent of time within an averaging interval (e.g., 30 min). The extent to which conditions conform to a steady state may be described using a variable

called relative non-stationarity,  $RN_{cov}$ , which is defined as the relative difference between the averaged 5-min and 30-min covariance values, given by (equations [4.36] to [4.38] in Foken, et al. 2012):

$$RN_{cov} = 100 \times \left| \frac{\frac{1}{6} \sum_{i=1}^6 (\overline{s'w'})_{ri} - (\overline{s'w'})_r}{(\overline{s'w'})_r} \right| \quad (F-1)$$

where  $s$  can be  $T_s$  for sonic temperature,  $T_c$  for corrected temperature,  $\rho_{co2}$  for CO<sub>2</sub> density,  $\rho_{h2o}$  for H<sub>2</sub>O density, or  $u$  or  $v$  for horizontal wind speed;  $w$  represents vertical wind velocity; subscript  $r$  indicates the variable after coordinate rotation; subscript  $i$  (for example, 1, 2, ..., or 6 if a 30-min averaging period is used) indicates the covariance of the  $i^{\text{th}}$  5 min interval within an averaging period; and the numerical number of 100 converts the relative non-stationarity into percent. Based on the calculated value of  $RN_{cov}$ , the steady state is classified into nine grades. Grade 1 is most steady and indicates highest data quality, whereas grade 9 is least steady and indicates relatively lower data quality (see TABLE F-1).

**TABLE F-1. Grades of relative non-stationarity, relative integral turbulence characteristics, and wind direction in the sonic instrument coordinate system.**

$RN_{cov}$ Relative non-stationarity [model (2.3) in Foken et al. (2012)]		$ITC_{sw}$ and $ITC_{tau}$ Relative integral turbulence characteristics [model (2.5) in Foken et al. (2012)]		$wnd\_dir\_sonic$ Wind direction	
Grade	Range (%)	Grade	Range (%)	Grade	Range
1 (highest)	[0 , 15)	1 (highest)	[0 , 15)	1 (highest)	[0 – 150°], [210 – 360°]
2	[15 , 30)	2	[15 , 30)	2	[150 – 170°], [190 – 210°]
3	[30 , 50)	3	[30 , 50)	3 (lowest)	[170 – 190°]
4	[50 , 75)	4	[50 , 75)		
5	[75 , 100)	5	[75 , 100)		
6	[100 , 250)	6	[100 , 250)		
7	[250 , 500)	7	[250 , 500)		
8	[500 , 1000)	8	[500 , 1000)		
9 (lowest)	$\geq 1,000\%$	9 (lowest)	$> 1,000\%$		

## F.2 Turbulent Conditions

Turbulence conditions are characterized using a term called integral turbulence characteristics ( $ITC$ ), which is defined as a standard deviation of a fluctuating variable (e.g., momentum variance or temperature variance) normalized by a scaling factor, for example, friction velocity or scaling temperature (Tilmann

1972). In a surface layer with fully developed turbulence, a given *ITC* term is a constant or at least follows a universal function of the scaling factor.

The most commonly used scaling factor is stability, defined as the ratio of aerodynamic height ( $z$ , sensor sensing height minus zero displacement height) to the Monin-Obukhov length ( $L$ ; Stull 1988, Kaimal and Finnigan 1994), or  $z/L$ . The other scaling factor used is (Thomas and Foken 2002):

$$\frac{z_+ f}{u_*} \quad (\text{F-2})$$

where  $f$  is the Coriolis parameter in  $\text{s}^{-1}$ ,  $u_*$  is friction velocity in  $\text{m s}^{-1}$ , and  $z_+$  is a constant in m that was introduced and set to “1” to make the scaling factor dimensionless. For a given site, the Coriolis parameter can be calculated using:

$$f = 2\Omega \sin \phi$$

where  $\Omega$  is angular velocity ( $7.292 \times 10^{-5} \text{ s}^{-1}$ ) and  $\phi$  is latitude (positive in the north hemisphere and negative in the south hemisphere).

*ITC* values have been accurately simulated using a well-known model (i.e., a function of the scaling factor) in conditions of fully developed turbulence. *ITC* may also be measured and then compared to the modeled *ITC* to show the degree to which turbulence has developed at that moment in time. The relative difference in percentage between the modeled and measured values are noted by  $ITC_\alpha$ , where the subscript  $\alpha$  indicates the variable of interest. When  $\alpha$  is vertical velocity,  $w$ , or horizontal wind speed,  $u$ ,  $ITC_\alpha$  is defined as follows:

$$ITC_\alpha = 100 \times \frac{\left| ITC_{\alpha\_model} - \left( \frac{\sqrt{(\alpha')^2}}{u_*} \right)_{measured} \right|}{ITC_{\alpha\_model}} \quad (\text{F-2})$$

where the  $ITC_{\alpha\_model}$  term is evaluated using:

$$ITC_{\alpha\_model} = \begin{cases} c_{\alpha 1} \ln \frac{z_+ f}{u_*} + c_{\alpha 2} & \frac{z}{L} > 0 \\ c_{\alpha 1} \left( \frac{z}{|L|} \right)^{c_{\alpha 2}} & \frac{z}{L} \leq 0 \end{cases} \quad (\text{F-3})$$

where  $c_{\alpha 1}$  and  $c_{\alpha 2}$  are parameters that depend on surface-layer stability (see TABLE F-2).

The relative difference in measured and theoretical *ITC* for temperature ( $T$ ) is noted by  $ITC_T$  and is given by (equation [4.41] in Foken et al. [2012]):

$$ITC_T = 100 \times \frac{ITC_{T\_model} - \left( \frac{\sqrt{(T'^2)_r}}{|T^*|} \right)_{measured}}{ITC_{T\_model}} \quad (F-4)$$

where  $T^*$  is scaling temperature, given by [equation (1.25b) in Kaimal and Finnigan (1994)]:

$$T^* = -\frac{\overline{T'w'}}{u_*} \quad (F-5)$$

and the  $ITC_{T\_model}$  term is evaluated using:

$$ITC_{T\_model} = c_{T1} \left( \frac{z}{|L|} \right)^{c_{T2}} \quad (F-6)$$

where  $c_{T1}$  and  $c_{T2}$  are parameters also depending on surface layer stability (see TABLE F-2).

TABLE F-2. Parameters in the model of integral turbulence characteristics (ITC). <sup>1/</sup>			
Variable in variance	$c_{a1}$	$c_{a2}$	$z/L$
Vertical velocity $a = W$	0.21	3.1	$0 < z/L < 0.4$
	1.3	0	$-0.032 < z/L \leq 0$
	2.0	1/8	$z/L \leq -0.032$
Horizontal wind speed $a = U$	0.44	6.3	$0 < z/L < 0.4$
	2.7	0	$-0.032 < z/L \leq 0$
	4.15	1/8	$z/L \leq -0.032$
Air temperature $a = T$	1.4	-1/4	$0.02 < z/L < 1$
	0.5	-1/2	$0.02 > z/L > -0.062$
	1.0	-1/4	$-0.062 > z/L > -1$
	1.0	-1/3	$-1 > z/L$
<sup>1/</sup> Summarized from Tables 4.2 and 4.3 in Foken et al. (2012)			

Similarly,  $ITC_{sw}$  is used to describe the turbulent conditions when measuring the covariance of a scalar,  $s$ , and vertical wind,  $w$ . However, instead of an explicit equation for  $ITC_{sw}$ , its value is conservatively estimated by setting it equal to  $ITC_T$  or  $ITC_w$ , whichever is greater; that is:

$$ITC_{sw} = \max(ITC_T, ITC_w) \quad (F-7)$$

$ITC_{sw}$  for fully developed turbulence conditions should be close to zero. The greater the value of  $ITC_{sw}$  becomes, the less developed the turbulence. Foken et al. (2012) suggested classifying the resulting value into nine grades, where grade 1 indicates conditions of fully developed turbulence, and grade 9 indicates conditions of undeveloped turbulence (see TABLE F-1).

Similarly, for momentum flux, a conservative approach is used:

$$ITC_{tau} = \begin{cases} \max(I TC_u, I TC_w) & \text{double rotations used} \\ I TC_w & \text{planar fit rotations used} \end{cases} \quad (F-8)$$

It should be noted that the variable  $u$  used in calculating  $ITC_u$  and  $ITC_{tau}$ , in the case of Table 4.2 of Foken et al. (2012), is streamwise wind speed, although the authors did not explicitly specify this. Accordingly, the raw variable  $U_x$  from a sonic anemometer, which is rarely a streamwise wind speed, must undergo coordinate rotations. It becomes the streamwise wind speed only after the first rotation of Tanner and Thurtell (1969) or the third rotation of Wilczak et al. (2001).

The data logger program uses either method of coordinate rotations, depending on the selection of the user; however, only the first two rotations of each method are done in order to reduce unnecessary computation time on the third rotation. Accordingly,  $u$  and subsequently  $ITC_u$  are only available to find  $ITC_{tau}$  if the method of Tanner and Thurtell (1969) is selected. If the planar fit method (Wilczak et al [2001]) is used,  $ITC_{tau}$  is simply found from  $ITC_w$  as an approximation (see equation F-8).

Similar to the other relative turbulence characteristics, the greater the value of  $ITC_{tau}$ , the less developed the turbulence. The resulting value is classified into nine grades, where grade 1 indicates fully developed conditions of turbulence, and grade 9 indicates least developed conditions of turbulence (see TABLE F-1).

Further, for stable surface-layer conditions beyond the ranges where parameters are defined in TABLE F-2, the quality grades for  $ITC_a$ ,  $ITC_T$ , and  $ITC_{tau}$  are conservatively assigned as 9.

### F.3 Wind Direction in the Sonic Instrument Coordinate System (wnd\_dir\_sonic)

The sonic anemometer has a boom-mount design that may affect the wind flow when the wind is blowing from behind the boom towards the sonic transducers. Accordingly, Foken et al. (2012) assigned a poorer data quality grade of 3 to wind coming from angles  $180 \pm 10^\circ$  relative to the sonic coordinate system, a medium grade of 2 to winds outside of this range but within  $29^\circ$  of  $180^\circ$ , and a good grade of 1 for all other angles (see TABLE F-1).

### F.4 Overall Quality Grade System

Each covariance variable over the averaging period is assigned an overall quality grade from 1 to 9 based on the individual grades of  $RN_{cov}$ ,  $ITC_{sw}$ , and

*wnd\_dir\_sonic* (see TABLE F-3). Grade 1 is the highest overall quality, and grade 9 is the poorest.

**TABLE F-3. Overall grades for each flux variable by the grades of relative non-stationary, relative integral turbulence characteristic, and wind direction in sonic instrument coordinate system.<sup>1/</sup>**

Overall quality grade	$RN_{cov}$ Relative non-stationarity	$ITC_{sw}$ Relative integral turbulence characteristic	wnd_dir_sonic Wind direction
1 (best)	1	1 – 2	1
2	2	1 – 2	1
3	1 – 2	3 – 4	1
4	3 – 4	1 – 2	1
5	1 – 4	3 – 5	1
6	5	5	2
7	6	6	2
8	7 – 8	7 – 8	2
9 (worst)	9	9	3

<sup>1/</sup>Simplified Table 4.5 in Foken et al. (2012)

## F.5 Programmatic Approach

The data logger program determines an overall quality grade using these steps:

1. Calculate quality variables:

$$RN_{cov} \text{ for } \overline{u'w'}, \overline{v'w'}, \overline{T_s'w'}, \overline{\rho_{co2}'w'}, \text{ and } \overline{\rho_{h2o}'w'}$$

$ITC_{tau}$  for momentum flux

$ITC_{Tsw}$  for sensible heat, CO<sub>2</sub>, and H<sub>2</sub>O fluxes

2. Use  $RN_{cov}$  to grade stationarity,  $ITC_{tau}$  and  $ITC_{Tsw}$  to grade the integral turbulence characteristics, and wind angle in the sonic coordinate system to grade wind direction (see TABLE F-2).
3. Define an array with three elements:

The first element records the best possible quality grade in the overall grade system for a given grade of relative non-stationarity. For example, a grade 2 for  $RN_{cov}$  can be assigned as grade 2 or 3 in the overall grade system. In this case, the data logger will store the value of **2** as the first element in the array.

Similarly, the second element in the array is the best possible quality grade in the overall grade system for a given grade of the integral turbulence characteristics.

The third element in the array is the best possible quality grade in the overall grade system for a given grade of wind direction.

4. The maximum value of the three elements is the overall quality grade for the variable being evaluated (such as, flux of CO<sub>2</sub>, H<sub>2</sub>O, sensible heat, or momentum).

## F.6 References

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# Appendix G. Footprint

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The percentage of measured scalar flux from an area of interest is a major indicator of appropriate site selection and station design. The upwind range within which the sources/sinks contribute a given percent of total fluxes (for example, 40, 55, and 90%) is typically desired by an investigator. Additionally, the location of sources/sinks that contributes most to the measured fluxes is often of interest (Kljun et al. 2004). These footprint characteristics can be calculated using a footprint function of the measured scalar flux.

A footprint function of measured scalar flux, given by  $f(x, y, z_m)$  where  $x$  and  $y$  are horizontal spatial variables with positive  $x$ -axis pointing into the streamwise direction and  $z_m$  is measurement height, is a probability spatial distribution of the relative contribution to the fluxes measured at the point  $(0, 0, z_m)$ , assuming that surface sources/sinks in the  $x$ - $y$  domain as described by  $F(x, y, 0)$  are horizontally homogenous, or in other words  $F(x, y, 0)$  is a constant. The footprint,  $f(x, y, z_m)$ , can be implicitly defined using the measured flux,  $F(0, 0, z_m)$ , and the flux spatial function at the surface,  $F(x, y, 0)$ , given by:

$$F(0, 0, z_m) = \int_{-\infty}^{\infty} \int_0^{\infty} F(x, y, 0) f(x, y, z_m) dx dy \quad (G-1)$$

The two functions inside the double integration describe the amount of contribution to the measured flux from sources/sinks across the integrated area. Given the two functions, the proportion of the measured flux from a smaller defined area can also be calculated. For a general case, this equation may be simplified by the assumption that  $F(x, y, 0)$  is a constant (in example, sources/sinks of flux are horizontally homogenous). The CRBasic online calculations are designed for this general case. Therefore,  $F(x, y, 0)$  is treated as a constant and only the footprint  $[f(x, y, z_m)]$  requires greater characterization.

To calculate the footprint in the CRBasic flux program, an analytical equation,  $f(x, y, z_m)$ , is needed. Several studies (Gash, 1986; Schuepp, et al., 1990; Schmid, 1994; Hsieh, et al., 2000; Kormann and Meixner, 2001; Kljun, et al, 2004) provide analytical footprint equations. The equations of Kljun, et al (2004) were developed more recently than the others, and accordingly are used in the CRBasic program. Their application, however, is limited to the following ranges of atmospheric stability, friction velocity, and measurement height:

1.  $-200 \leq (z_m - d) / L \leq 1$
  2.  $u_* \geq 0.2$
  3.  $z_m - d \geq 1 \text{ m}$
- (G-2)

where  $d$  is zero displacement height and  $L$  is Monin-Obukhov length. For cases outside of the ranges above, the analytical footprint equation of Kormann and Meixner (2001) is used.

## G.1 Kljun, et. al. (2004) Analytical Footprint Equations

### G.1.1 Models and Parameters

By applying dimensional analysis (Buckingham  $\Pi$  method, see Stull 1988) and analyzing numerical simulations, Kljun et al (2004) summarized footprints in field scale for a given roughness length ( $z_0$ ) and ratio of aerodynamic height to planetary boundary-layer (PBL) height as a dimensionless footprint ( $F_*$ ) in terms of dimensionless length ( $X_*$ ) for the range of conditions presented in (G-2). The summarized footprint is represented by the model:

$$F_*(X_*) = k_1 \left( \frac{X_* + k_4}{k_3} \right)^{k_2} \exp \left[ k_2 \left( 1 - \frac{X_* + k_4}{k_3} \right) \right] \quad (\text{G-3})$$

where  $k_i$  (subscript  $i = 1, 2, 3$ , and 4) is a parameter. If the parameters in the model are given, the dimensionless footprint can be calculated for different dimensionless lengths. These parameters can be statistically estimated using the sampled values of  $X_*$  and  $F_*$ . The dimensionless length is a combination of vertical wind standard deviation ( $\sigma_w$ ), friction velocity ( $u_*$ ), measurement aerodynamic height ( $z$ ), and streamwise distance to measurement location ( $x$ ), given by:

$$X_* = \left( \frac{\sigma_w}{u_*} \right)^{a_1} \frac{x}{z} \quad (\text{G-4a})$$

where  $a_1$  is a parameter that was found to be 0.8 by numerical simulations using the software *LPDM-B*. To consider the zero displacement height ( $d$ ) over different surface types, the variable  $z$  should be interpreted as the measurement aerodynamic height ( $z = z_m - d$ ), which was confirmed by Dr. Kljun per email on November 14, 2014. The dimensionless footprint of  $F_*$  is a combination of vertical wind standard deviation, friction velocity, planetary boundary-layer height ( $h$ ), measurement aerodynamic height, and streamwise footprint integrated over cross-wind (i.e., marginal streamwise footprint) at a field scale [ $f_y(x, z)$  in  $\text{m}^{-1}$ ], given by:

$$F_* = \left( \frac{\sigma_w}{u_*} \right)^{a_2} \left( 1 - \frac{z}{h} \right)^{-1} z f_y(x, z) \quad (\text{G-4b})$$

where  $a_2$  is a parameter that was found to be -0.8 by simulation using the software *LPDM-B*.

For a given case, the values of  $\sigma_w$ ,  $u_*$ ,  $h$ , and  $z$  are known and the value of  $f_y(x, z)$  can be numerically simulated (Horst and Weil 1992). Given these values,  $X_*$  and  $F_*$  can be calculated using (G-4a) and (G-4b). Kljun, et al (2004) then used calculated values of dimensionless footprint and dimensionless length as samples to statistically estimate the parameters of  $k_1$  to

$k_4$  in model (G3) for four roughness lengths and four ratios of aerodynamic height to PBL height as shown in TABLE G-1.

<b>TABLE G-1. Estimated parameters in dimensionless footprint model (F3)</b>								
z/h	$k_1$	$k_2$	$k_3$	$k_4$	$k_1$	$k_2$	$k_3$	$k_4$
	$z_0 = 0.01 \text{ m}$				$z_0 = 0.1 \text{ m}$			
0.005	0.024	3.84	31.0	18.0	0.028	2.47	22.0	12.0
0.075	0.024	4.11	33.0	15.0	0.027	2.87	24.0	10.0
0.250	0.021	3.61	35.0	12.0	0.026	3.40	27.0	10.0
0.500	0.025	4.23	33.0	9.0	0.028	5.06	32.0	12.0
	$z_0 = 0.30 \text{ m}$				$z_0 = 1.0 \text{ m}$			
0.075	0.042	4.06	19.0	7.00	0.052	2.40	11.0	5.00
0.250	0.038	4.24	21.0	7.00	0.050	3.19	14.0	4.00
0.500	0.042	6.02	23.0	6.00	0.051	3.93	15.0	3.00

Even without the PBL height, it is possible to use these parameters. From figure 7 in Kljun et al (2004) it is evident that  $k_1$  can be well described using a function of the natural logarithm of  $z_0$ , which is independent of  $z/h$ . This function is given by (left-top panel in figure 7, equation 13 in Kljun et al [2004], and email from Dr. Kljun in Feb 10, 2015).

$$k_1 \approx \frac{0.175}{3.418 - \ln z_0} \quad (\text{G-5a})$$

Parameters  $k_3$  and  $k_4$  are both linear functions of  $\ln z_0$ . Parameter  $k_3$  is given by (left bottom panel in figure 7 and equation 15 in Kljun et al [2004]).

$$k_3 \approx 4.277 \times (3.418 - \ln z_0) \quad (\text{G-5b})$$

and parameter  $k_4$  is given by (right bottom panel in figure 7 and equation 16 in Kljun et al [2004]).

$$k_4 \approx 1.685 \times (3.418 - \ln z_0) \quad (\text{G-5c})$$

#### NOTE

Although the parameters published in Kljun et al. (2004) had fewer significant digits, email correspondence with Dr. Kljun dated Feb 10, 2015, led to the adoption of three digits after the decimal for parameters in Equation G-5a through G-4c.

Parameter  $k_2$  is independent of  $z_0$  and is a constant. Determining its value requires taking the integral of  $\hat{F}_*(\hat{X}_*)$  (the over-hat indicates they are equations with statistically-estimated parameters) over the entire domain of  $\hat{X}_*$  and setting it equal to one, as shown here (see appendix in Kljun et al. [2004]):

$$\int_{k_4}^{\infty} \hat{F}_*(\hat{X}_*) d\hat{X}_* = k_1 k_3 \exp(k_2) k_2^{-k_2} \Gamma(k_2) = 1 \quad (\text{G-5d})$$

Substituting (G-5a) and (G-5b) into (G-5d) leads to:

$$\exp(k_2) k_2^{-k_2} \Gamma(k_2) = 1.336050 \quad (\text{G-5e})$$

A numerical solution then generates  $k_2$ :

$$k_2 = 3.682540 \quad (\text{G-5f})$$

## G.1.2 Application of Analytical Footprint

The marginal streamwise footprint  $[f_y(x, z)]$  in (G-4b) is required to calculate the needed footprint characteristics. However, for many years its analytical form and the resulting cumulative footprint were unavailable for a wide range of stabilities and wind velocity profiles. This motivated several studies to conduct numerical simulations (Hsieh et al. 2000, Kljun et al 2004), which could then be used to develop analytical footprint equations (for example model [G3] and TABLE G-1).

Given an analytical form of  $f_y(x, z)$ , the calculation of footprint characteristics is straight forward. The sections below present equations for footprint characteristics such as the percentage of flux from a defined upwind range of interest and the point of maximum source/sink contribution to the measured flux. These equations relate  $f_y(x, z)$ ,  $F_*(X_*)$ , and footprint characteristics.

### Percentage of measured scalar flux from the upwind range of interest

Given the marginal streamwise footprint  $f_y(x, y)$ , the percentage of contribution from the sources/sinks within the upwind range of  $R$ ,  $[P_F(R)]$ , can be calculated using:

$$p_F(R) = 100 \int_{-R_{k4}}^R f_y(x, z) dx \quad (\text{G-6})$$

where  $-R_{k4}$  is the downwind location of starting contribution of sources/sinks to measured fluxes.

Since:

$$\int_{-R_{k4}}^R f_y(x, z) dx = \frac{\left(\frac{\sigma_w}{u_*}\right)^{a_2} \left(1 - \frac{z}{h}\right)^{-1} z \int_{-R_{k4}}^R f_y(x, z) dx}{\left(\frac{\sigma_w}{u_*}\right)^{a_2} \left(1 - \frac{z}{h}\right)^{-1} z}$$

$$= \left(\frac{\sigma_w}{u_*}\right)^{-a_2} \frac{1}{z} \left(1 - \frac{z}{h}\right) \int_{-R_{k4}}^R \hat{F}_*(\hat{X}_*) dx \quad (\text{G-7})$$

and because  $F_*(X_*)$  is defined in the domain of  $X_* > -k_4$ , this low limit of integration is the value of  $x$  at  $X_*(x) = -k_4$ . Thus,  $R_{k4}$  is given by:

$$R_{k4} = k_4 z \left(\frac{u_*}{\sigma_w}\right)^{a_1} \quad (\text{G-8})$$

Submitting (G-7) into (G-6) generates:

$$p_F(R) = 100 \left(\frac{\sigma_w}{u_*}\right)^{-a_2} \frac{1}{z} \left(1 - \frac{z}{h}\right) \int_{-R_{k4}}^R F_*[X_*(x)] dx \quad (\text{G-9})$$

Calculation for this is possible using numerical integration of the dimensionless footprint  $F_*[X_*(x)]$  at discrete, incremental values of  $x$ , starting at a low value given by  $-R_{k4}$  and increasing until the value for  $R$  is reached. Specifically, the value for dimensionless footprint at each value of  $x$  is found by using equations (G-3) and (G-4a) with measured variables ( $\sigma_w$  and  $u_*$ ), known variables ( $z$ ), and estimated parameters [ $k_i$ , given by (G-5a), (G-5b), (G-5c), and (G-5f)], as shown here:

$$F_*[X_*(x)] = k_1 \left[ \frac{\left(\frac{\sigma_w}{u_*}\right)^{0.8} \frac{x}{z} + k_4}{k_3} \right]^{k_2} \exp \left\{ k_2 \left[ 1 - \frac{\left(\frac{\sigma_w}{u_*}\right)^{0.8} \frac{x}{z} + k_4}{k_3} \right] \right\} \quad (\text{G-10})$$

The values for dimensionless footprint at every interval of  $x$  may then be summed to estimate the value of the integral term in equation (G-9) for calculation of  $p_F(R)$ .

**Upwind location of source/sink that contributes most to the measured flux**  
Differentiating both sides of (G-4b) with respect to  $x$  generates:

$$\frac{df_y(x, z)}{dx} = \left(\frac{\sigma_w}{u_*}\right)^{-a_2} \left(1 - \frac{z}{h}\right) z^{-1} \frac{dF_*}{dX_*} \frac{dX_*}{dx} \quad (\text{G-11})$$

The marginal streamwise footprint  $[f_y(x, z)]$  is a bell-shape function with respect to  $x$ , with a maximum occurring at  $x_{max}$ , which follows that:

$$\left. \frac{df_y(x, z)}{dx} \right|_{x=x_{max}} = 0 \quad (G-12)$$

For real-world cases in the field, the terms of measured variables in the right-hand-side of (G-11) will never equal zero, therefore, equation (G-12) can only be true when the last two derivative terms are evaluated as zero at  $x_{max}$ , that is:

$$\left. \frac{dF_*}{dX_*} \frac{dX_*}{dx} \right|_{x=x_{max}} = 0 \quad (G-13)$$

This can be expanded to the following equation:

$$\left. \frac{dF_*}{dX_*} \frac{dX_*}{dx} \right|_{x=x_{max}} = \frac{k_1 k_2}{k_3 z} \left( \frac{\sigma_w}{u_*} \right)^{a_1} \left[ \frac{X_*(x_{max}) + k_4}{k_3} \right]^{k_2 - 1} \exp \left[ k_2 \left( 1 - \frac{X_*(x_{max}) + k_4}{k_3} \right) \right] \left[ 1 - \frac{X_*(x_{max}) + k_4}{k_3} \right] = 0$$

This equation is then solved for  $X_*(x_{max}) > -k_4$ , resulting in the upwind distance from the measurement station to the location that contributes most to the measured flux being expressed as:

$$x_{max} = (k_3 - k_4) z \left( \frac{u_*}{\sigma_w} \right)^{0.8} \quad (G-14)$$

According to (G-6) and (G-9), the percentage of contribution to the measured flux within an upwind range of  $x_p$ , where subscript  $p$  indicates percent and can have a value of 0 to 100 [e.g.,  $P_F(x_{10}) = 10$  and  $P_F(x_{90}) = 90$ ], can be expressed as:

$$p_F(x_p) = 100 \left( \frac{\sigma_w}{u_*} \right)^{0.8} \frac{1}{z} \left( 1 - \frac{z}{h} \right) \int_{-R_{i4}}^{x_p} F_*[X_*(x)] dx \quad (G-15)$$

This is an increasing monotonic function of  $x_p$ . Given this, for a value of  $p_F(x_p)$ , only one value of  $x_p$  can be found. The value of  $x_p$  may be estimated by performing a numerical integration of  $p_F(R)$  as described in the section above. Using a subscript  $i$  for  $x$  indicates the sequential number of numerical integration steps, the two neighbor values of  $p_F(x_i)$  less than the target value of  $p$  (for example,  $p = 10$ ) and  $p_F(x_{i+1})$  greater than the target value can then be used to interpolate a more precise value of  $x_p$  where  $P_F(x_p) = p$ .

### G.1.3 Programmatic Approach

#### Roughness length

Applying model (G3) requires knowing the roughness length in order to calculate the parameters (G-5a) to (G-5c). The roughness length depends on surface type (for example, bare land, water surface, crops, grasses, trees, and shrubs) and is approximately  $0.13h_c$  for crops and grasses, where  $h_c$  represents canopy height (Tanner and Pelton, 1960; Stanhill, 1969),  $0.06h_c$  for forests (Jarvis, et al., 1976; Raupach, et al., 1991), and  $0.033h_r$ , where  $h_r$  represents roughness element height for bare land (for example, sands) (Raupach, et al., 1991). A more accurate value of roughness length depends not only on the surface type but also on surface roughness texture (for a canopy, this texture can be described using vegetative surface area per unit volume). However, this texture, the canopy height, and the resulting roughness length may change quickly during certain periods of the growing season. This makes it impractical to input a single roughness length that will be valid for a long time periods. Accordingly, the roughness length should be updated periodically, which is possible using the well-known equation of a wind profile under neutral conditions [equation (4.2) in Rosenberg et al. (1983)]:

$$z_0 = (z_m - d) \exp \left( - \frac{k \sqrt{\bar{u}^2 + \bar{v}^2}}{u_*} \right) \quad (\text{G-16})$$

where  $k$  is von Karman constant (0.41) and  $\bar{u}$  and  $\bar{v}$  are the two orthogonal components of mean horizontal wind speeds, respectively. The roughness length is automatically updated by the data logger at the end of each averaging interval as long as the surface layer stability is under neutral conditions, as defined by the strict criterion of  $|z / L| < 0.02$  (Hsieh et al. 2000). The updated roughness length will then be used for the calculation of parameters  $k_1$ ,  $k_3$ , and  $k_4$  using (G-5a) to (G-5c).

Until an averaging period occurs with neutral stability, an initial value for roughness length must be estimated and used. Accordingly, our programmatic approach is to require that the user select, among the options in a menu, the land type that most closely matches the area around their eddy covariance station. The program then uses this input to calculate an initial roughness length as follows:

$$z_0 = 10^{0.997 \log_{10} h_c - 0.883} \quad (\text{G-17})$$

for crops and grasses (Szeicz et al 1969),  $0.06h_c$  for forests and shrubs, and 0.01 m for bare land and water surfaces (i.e., corresponds to the parameters for lowest roughness length in TABLE G-1). As soon as measured half-hourly data are available and the stability is under neutral conditions, this initial roughness length will be updated using (G-16).



**Calculation for parameters of  $k_1$  to  $k_4$** 

$$k_1 \approx \frac{0.175}{3.418 - \ln z_0}$$

$$k_2 \approx 3.682540$$

$$k_3 \approx 4.277 (3.418 - \ln z_0)$$

$$k_4 \approx 1.685 (3.418 - \ln z_0)$$

**Calculation of planetary boundary-layer height**

<b>TABLE G-2. Relationship of Monin-Obukhov length (L) to planetary boundary-layer height (h)</b>							
<b>L (m)</b>	-5	-30	-650	$\infty$	1000	130	84
<b>h (m)</b>	2000	1500	1200	1000	800	250	200

The Monin-Obukhov length is calculated in eddy covariance flux measurements, and then it is used to find the PBL height using the data points in TABLE G-2 and linear interpolation.

**Upwind location of source/sink that contributes most to the measured flux (maximum location)**

The following equation is used in the data logger:

$$x_{\max} = (k_3 - k_4) z \left( \frac{u_*}{\sigma_w} \right)^{0.8}$$

**Upwind inflection points of footprint**

The footprint is a bell-shaped function with one maximum point (turning point) and two inflection points. Because the footprint changes most in the segments from the left inflection point ( $x_{IL}$ ) to  $x_{\max}$  and from  $x_{\max}$  to the right inflection point ( $x_{IR}$ ), these inflection points may be used as boundaries for special numerical integration segments where the integration intervals are smaller to provide greater accuracy. Outside of these special segments, the integration intervals may be larger and thereby decrease the computation required. Specifically, the inflection point located at the left side of  $x_{\max}$  ( $x_{IL}$ ) is given as:

$$x_{IL} = \frac{x_{\max}}{k_3 - k_4} \left[ k_3 \left( \frac{\sqrt{k_2} - 1}{\sqrt{k_2}} \right) - k_4 \right]$$

and the other is at the right side of  $x_{\max}$  ( $x_{IR}$ ):

$$x_{IR} = \frac{x_{\max}}{k_3 - k_4} \left[ k_3 \left( \frac{\sqrt{k_2} + 1}{\sqrt{k_2}} \right) - k_4 \right]$$

See the derivation of the inflection points in Appendix G.2, *Derivation of Equations for Upwind Locations at Inflection Points of Footprint in Kljun et al (2004) (p. G-10)*.

#### Percentage of measured scalar flux from the upwind rand of interest to measurements

As explained previously, the percentage of measured flux coming from an area of interest may be calculated with the data logger using the following equation:

$$p_F(R) = 100k_1 \left( \frac{\sigma_w}{u_*} \right)^{0.8} \frac{1}{z} \left( 1 - \frac{z}{h} \right) \int_{-R_{k4}}^R \left[ \frac{\left( \frac{\sigma_w}{u_*} \right)^{0.8} \frac{x}{z} + k_4}{k_3} \right]^{k_2} \exp \left\{ k_2 \left[ 1 - \frac{\left( \frac{\sigma_w}{u_*} \right)^{0.8} \frac{x}{z} + k_4}{k_3} \right] \right\} dx$$

where the integral is evaluated using numerical integration.

Within the first integration segment (from  $R_{k4}$  to  $x_{IL}$ ), the trapezoidal rule for numerical integration is used with the segment divided into  $q$  intervals, where  $q$  is an integer selected such that the resolution of the numerical integration yields reasonable accuracy without a large burden in computation (for example,  $q = 20$ ).

Within the second segment ( $x_{IL}$  to  $x_{max}$ ), the trapezoidal rule is still used with an integration interval of  $(x_{max} - x_{IL})/q$ .

The third segment also uses the trapezoidal rule and extends from  $x_{max}$  to  $x_{IR} + (x_{IR} - x_{max})$  with an integration interval of  $(x_{IR} - x_{max})/q$ . The fourth and final segment begins at the end of the 3<sup>rd</sup> segment. The fourth segment uses integration intervals with a size of  $4z$ . Although these intervals may be significantly larger than the intervals used in the other segments, the integration accuracy should still be acceptable since Boole's rule, rather than the trapezoidal rule, is used within this segment and the slope of the footprint should be changing very slowly throughout the segment. The fourth segment initially extends to  $200z$  beyond the segment starting point or until the the cumulative flux reaches 90%. If the distance of interest is not reached at the end of the fourth segment but is within another  $100z$ , an additional 25 integration intervals are added to the segment, with the endpoint being the distance of interest. If the distance of interest is beyond another  $100z$ , it is assumed that the cumulative footprint would be wholly contained within the distance of interest, thus 99% is reported as the cumulative flux within the distance of interest. If the cumulative flux never reaches 90%, which is possible under certain conditions where the numerical integration is inadequate or the model does not truly reflect the real footprint distribution, the distance for 90% flux will be reported as *NAN* (not a number).

Scaling the integration intervals within each segment provides a way to have higher integration resolution when the slope of footprint changes more dramatically while still limiting the size of the integration interval when the slope is not changing as much. This approach is successful in converging the percentage flux to a value of one if numerically integrated over the entire domain. An additional advantage of this approach is that because  $x_{max}$  must be used as a segment boundary, the peak value of the function is never missed, which contributes to greater accuracy of the overall numerical integration.

**Upwind range within which the sources/sinks contributes a given percent to measured flux**

If this upwind range is denoted using  $x_p$  where subscript  $p$  indicates the given percent, it can be implicitly expressed in an equation as:

$$p = 100k_1 \left( \frac{\sigma_w}{u_*} \right)^{0.8} \frac{1}{z} \left( 1 - \frac{z}{h} \right) \int_{-R_{i4}}^{x_p} \left[ \frac{\left( \frac{\sigma_w}{u_*} \right)^{0.8} \frac{x}{z} + k_4}{k_3} \right]^{k_2} \exp \left\{ k_2 \left[ 1 - \frac{\left( \frac{\sigma_w}{u_*} \right)^{0.8} \frac{x}{z} + k_4}{k_3} \right] \right\} dx$$

Among the values of  $p_F(x_p)$  that were found in the process of numerical integration described above, if the value in current iteration is just greater than the target percentage (for example,  $p = 40$ ), a more precise value of  $x_{40}$  [for example,  $p_F(x_{40}) = 40$ ] can be interpolated using this value along with the value in previous iteration. In this way,  $x_{40}$ ,  $x_{55}$ , and  $x_{90}$  are found.

## G.2 Derivation of Equations for Upwind Locations at Inflection Points of Footprint in Kljun et al. (2004)

As described above, integration segment boundaries should be determined by the upwind inflection points of the footprint. Since the footprint is known to be a bell-shaped function, there is one maximum point ( $x_{max}$ ) and two inflection points ( $x_{IL}$  and  $x_{IR}$ ) on both sides of the maximum, respectively. Accordingly,  $x_{max}$  may be found by setting the first order derivative of the footprint function to zero. Similarly,  $x_{IL}$  and  $x_{IR}$  may be found by setting the second order derivative to zero. The following section shows this derivation for these points.

### G.2.1 Footprint Model

The footprint in Kljun et al. (2004) is given in the form of a dimensionless footprint [ $F_*(X_*)$ ]:

$$F_*(X_*) = k_1 \left( \frac{X_* + k_4}{k_3} \right)^{k_2} \exp \left[ k_2 \left( 1 - \frac{X_* + k_4}{k_3} \right) \right] \quad (G-18)$$

where  $k_i$  (subscript  $i = 1, 2, 3$ , and  $4$ ) is a parameter, and  $X_*$  is the dimensionless length. It is a combination of vertical wind standard deviation ( $\sigma_w$ ), friction velocity ( $u_*$ ), measurement aerodynamic height ( $z = z_m - d$ ), and the upwind distance ( $x$ ) from the measurement location given by:

$$X_* = \left( \frac{\sigma_w}{u_*} \right)^{a_1} \frac{x}{z} \quad (G-19)$$

where  $a_1$  is a parameter. The dimensionless footprint of  $F_*$  is a combination of vertical wind standard deviation, friction velocity, planetary boundary-layer height ( $h$ ), measurement aerodynamic height, and streamwise footprint

integrated over cross-wind (i.e., marginal streamwise footprint) at a field scale [ $f_y(x, z)$  in  $\text{m}^{-1}$ ], given by:

$$F_* = \left( \frac{\sigma_w}{u_*} \right)^{a_2} \left( 1 - \frac{z}{h} \right)^{-1} z f_y(x, z) \quad (\text{G-20})$$

where  $a_2$  is a parameter.

## G.2.2 Upwind location of maximum footprint

Differentiating both sides of (G-20) with respect to  $x$  generates:

$$\frac{df_y(x, z)}{dx} = \left( \frac{\sigma_w}{u_*} \right)^{-a_2} \left( 1 - \frac{z}{h} \right) z^{-1} \frac{dF_*}{dX_*} \frac{dX_*}{dx} \quad (\text{G-21})$$

The derivative of dimensionless length with respect to  $x$  is greater than zero and is independent of  $x$ ; therefore:

$$\frac{df_y(x, z)}{dx} = 0 \text{ at } \frac{dF_*}{dX_*} = 0 \quad (\text{G-22})$$

which indicates  $f_y(x, z)$  and  $F_*$  reaches the maximum at the same upwind location ( $x_{\max}$ ). Therefore, the location of maximum footprint satisfies the following equation:

$$\left. \frac{dF_*}{dX_*} \right|_{X=X_{\max}} = \frac{k_1 k_2}{k_3} \left[ \frac{X_*(x_{\max}) + k_4}{k_3} \right]^{k_2-1} \exp \left[ k_2 \left( 1 - \frac{X_*(x_{\max}) + k_4}{k_3} \right) \right] \left[ 1 - \frac{X_*(x_{\max}) + k_4}{k_3} \right] = 0 \quad (\text{G-23})$$

Solving this equation for  $X_*(x_{\max}) > -k_4$  generates:

$$x_{\max} = (k_3 - k_4) z \left( \frac{u_*}{\sigma_w} \right)^{0.8} \quad (\text{G-24})$$

## G.2.3 Upwind locations of inflection points

Differentiating both sides of (G-21) with respect to  $x$  generates:

$$\frac{d^2 f_y(x, z)}{dx^2} = \left( \frac{\sigma_w}{u_*} \right)^{-a_2} \left( 1 - \frac{z}{h} \right) z^{-1} \frac{d^2 F_*}{dX_*^2} \left( \frac{dX_*}{dx} \right)^2 \quad (\text{G-25})$$

The derivative of dimensionless length with respect to  $x$  is greater than zero and is independent of  $x$ ; therefore:

$$\frac{d^2 f_y(x, z)}{dx^2} = 0 \text{ at } \frac{d^2 F_*}{dX_*^2} = 0 \quad (\text{G-26})$$

which indicates  $f_y(x, z)$  and  $F_*$  have inflection points at the same upwind locations, and therefore:

$$\frac{d^2 F_*}{dX_*^2} = 0 \quad (\text{G-27})$$

This can be used to find the upwind locations of the inflection points in the footprint curve.

Referencing (G-23), the first order derivative of dimensionless footprint can be written as:

$$\frac{dF_*}{dX_*} = \frac{k_2}{k_3} \left[ \left( \frac{X_* + k_4}{k_3} \right)^{-1} - 1 \right] F_* \quad (\text{G-28})$$

Using this equation, the derivative at the second order can be derived as:

$$\begin{aligned} \frac{d^2 F_*}{dX_*^2} &= \frac{k_2}{k_3} \left[ -\frac{1}{k_3} \left( \frac{X_* + k_4}{k_3} \right)^{-2} F_* + \left( \frac{X_* + k_4}{k_3} \right)^{-1} \frac{dF_*}{dX_*} - \frac{dF_*}{dX_*} \right] \\ &= -\frac{k_2}{k_3^2} \left( \frac{X_* + k_4}{k_3} \right)^{-2} F_* + \frac{k_2^2}{k_3^2} \left[ \left( \frac{X_* + k_4}{k_3} \right)^{-1} - 1 \right]^2 F_* \\ &= -\frac{k_2}{k_3^2} F_* \left\{ \left( \frac{X_* + k_4}{k_3} \right)^{-2} + k_2 \left[ \left( \frac{X_* + k_4}{k_3} \right)^{-1} - 1 \right]^2 \right\} \end{aligned} \quad (\text{G-29})$$

In this equation, the term ahead of the curly bracket is not zero. Therefore, in order to satisfy (G-27), the term inside the curly bracket must be zero. If assuming:

$$X = \left( \frac{X_* + k_4}{k_3} \right)^{-1} \quad (\text{G-30})$$

The term inside the curly bracket satisfies (G-27) in the following form:

$$X^2 + k_2 [X - 1]^2 = 0 \quad (\text{G-31})$$

Solving this equation, substituting (G-19) into  $X$ , and referencing (G-24) leads to an equation for the left inflection point:

$$x_{IL} = \frac{x_{\max}}{k_3 - k_4} \left[ k_3 \left( \frac{\sqrt{k_2} - 1}{\sqrt{k_2}} \right) - k_4 \right] \quad (\text{G-32})$$

Similarly, the equation for the right inflection point is obtained by:

$$x_{IR} = \frac{x_{\max}}{k_3 - k_4} \left[ k_3 \left( \frac{\sqrt{k_2} + 1}{\sqrt{k_2}} \right) - k_4 \right] \quad (\text{G-33})$$

## G.3 Kormann and Meixner (2001) Analytical Footprint Equations

### G.3.1 Footprint

As an alternative to the analytical approach used by Kljun, et al., (2004), which is limited by the conditions presented in (G-2), the footprint was derived by Kormann and Meixner (2001) based on Van Ulden (1978) as [(see the detailed derivations in Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19)]:

1. Two-dimensional (2D) marginal streamwise footprint

$$f_y(x, z) = \frac{1}{\Gamma(\mu)} \xi^\mu \left( \frac{z^{m+1}}{x^{\mu+1}} \right) \exp \left( -\xi \frac{z^r}{x} \right) \quad (\text{G-34})$$

where  $r$ ,  $\mu$ , and  $\xi$  are composites of other variables which have been combined for succinctness in the expression. Each of these variables is defined below.

$r$  (shape factor):

$$r = 2 + m - n \quad (\text{G-35})$$

where  $m$  is the exponent in a vertical profile of horizontal wind [see (G-74) in Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19)], and  $n$  is the exponent in a vertical profile of eddy diffusivity [see (G-63) in Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19)].

$\mu$ :

$$\mu = \frac{m+1}{r} \quad (\text{G-36})$$

$\xi$ :

$$\xi = \frac{U}{\kappa z^2} \quad (\text{G-37})$$

where  $U$  is the wind constant in a vertical profile of horizontal wind [see (G) in74 Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19)], and  $\mathbf{K}$  is the constant in power-law profile of the eddy diffusivity.

$$\mathbf{K} = \frac{ku_* z^{1-n}}{\varphi_c (z/L)} \quad (\text{G-38})$$

The calculations for the variables:  $m$ ,  $n$ ,  $U$ , and  $\mathbf{K}$  will be given in the following sections.

### G.3.2 Programmatic Approach

The 3D footprint  $[f(x, y, z)]$  can be expressed in terms of a marginal streamwise footprint and a *down-wind* probability distribution of scalar concentrations from *upwind* sources in a domain of  $x$  and  $y$   $[c(x, y)]$  [see model (9) in Horst and Weil, (1992) and model (8) in Kormann and Meixner, (2001)], given by:

$$f(x, y, z) = c(x, y) f_y(x, z) \quad (\text{G-39})$$

where:

$$c(x, y) = \frac{\bar{u}(x)}{\sqrt{2\pi x \sigma_y}} \exp \left[ -\frac{1}{2} \left( \frac{y \bar{u}(x)}{x \sigma_y} \right)^2 \right] \quad (\text{G-40})$$

where the constant  $\sigma_y$  is the standard deviation of crosswind scalar concentration and  $\bar{u}(x)$  is the effective velocity of the scalar plume. This equation is derived from model (10) in Horst and Weil (1992) and model (9) in Kormann and Meixner (2001) after the simple scalar dispersion ( $\sigma$ ) in the model is replaced with a detailed descriptive dispersion  $[\sigma_y x / \bar{u}(x)]$ , which depends on distance from the station ( $x$ ) and effective velocity of the scalar plume  $[\bar{u}(x)]$ . Substituting (G-34) and (G-40) into (G-39) leads to the three-dimensional footprint:

$$f(x, y, z) = \frac{\bar{u}(x)}{\sqrt{2\pi \sigma_y} \Gamma(\mu)} \xi^\mu \left( \frac{z^{m+1}}{x^{\mu+2}} \right) \exp \left[ -\frac{1}{x^2} \left( \xi x z^r + \frac{1}{2} \left( \frac{y \bar{u}(x)}{\sigma_y} \right)^2 \right) \right] \quad (\text{G-41a})$$

where:

$$\bar{u}(x) = U \frac{\Gamma(\mu)}{\Gamma\left(\frac{1}{r}\right)} \left( \frac{\mathbf{K} r^2}{U} x \right)^{\frac{m}{r}} \quad (\text{G-41b})$$

See (G-82) to (G-92) in Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19), for associated derivations.

### G.3.3 Application of analytical footprint

Unlike the dimensionless footprint in Kljun et al., (2004), the footprint developed by Kormann and Meixner, (2001) explicitly gives the analytical marginal (cross-wind integrated) streamwise footprint (G-34) and three-dimensional footprint (G-41a and G-41b). Both can be directly used to calculate the footprint characteristics.

#### Percentage of measured scalar flux from the upwind range of interest

The percentage of contribution from these sources/sinks, within the upwind range of interest, to the measured flux [ $p_F(R)$ ] is given by:

$$\begin{aligned} p_F(R) &= 100 \int_0^R f_y(x, z) dx \\ &= 100 \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \lim_{\Delta x \rightarrow 0} \int_{0+\Delta x}^R \frac{1}{x^{\mu+1}} \exp\left(-\xi \frac{z^r}{x}\right) dx \end{aligned} \quad (G-42)$$

where the Gamma function of  $\mu$  can be accurately approximated using Memes (2010):

$$\Gamma(\mu) \approx \sqrt{\frac{2\pi}{\mu}} \left[ \frac{1}{e} \left( \mu + \frac{1}{12\mu - \frac{1}{10\mu}} \right) \right]^\mu \quad (G-43)$$

#### Location of source/sink that contributes most to the measured flux

1. Approach using 2D marginal streamwise footprint [ $f_y(x, z)$ ]

Differentiating (G-34) with respect to  $x$  generates:

$$\begin{aligned} \frac{df_y(x, z)}{dx} &= \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \frac{d}{dx} \left[ \frac{1}{x^{\mu+1}} \exp\left(-\xi \frac{z^r}{x}\right) \right] \\ &= \frac{\xi^\mu z^{m+1}}{\Gamma(\xi)} \exp\left(-\xi \frac{z^r}{x}\right) \left\{ \frac{-(\mu+1)}{x^{\mu+2}} + \frac{\xi z^r}{x^{\mu+3}} \right\} \\ &= \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \exp\left(-\xi \frac{z^r}{x}\right) \left[ \frac{\xi z^r - x(\mu+1)}{x^{\mu+3}} \right] \end{aligned} \quad (G-44)$$

The marginal streamwise footprint [ $f_y(x, z)$ ] is a bell-shape function with respect to  $x$ , with the maximum found at  $x_{max}$ , which follows that:

$$\left. \frac{df_y(x, z)}{dx} \right|_{x=x_{max}} = 0 \quad (G-45)$$



All terms except for the term in the square bracket in (G-43) are greater than zero for any real-world case in the field, and therefore setting that term equal to zero results in the solution for  $x_{max}$ :

$$x_{max} = \frac{\xi z^r}{\mu + 1} \quad (G-46)$$

## 2. Approach using 3D footprint $[f(x,y,z)]$

Differentiating (G-41a) with respect to  $x$  at  $y = 0$

$$\begin{aligned} \frac{df(x, 0, z)}{dx} &= \frac{\xi^\mu z^{m+1}}{\sqrt{2\pi}\sigma_y \Gamma(\mu)} \frac{d}{dx} \left[ \frac{\bar{u}(x)}{x^{\mu+2}} \exp\left(-\xi \frac{z^r}{x}\right) \right] \\ &= \frac{\xi^\mu z^{m+1}}{\sqrt{2\pi}\sigma_y \Gamma(\mu)} \exp\left(-\xi \frac{z^r}{x}\right) \left\{ \frac{1}{x^{\mu+2}} \frac{d\bar{u}(x)}{dx} - \frac{(\mu+2)\bar{u}(x)}{x^{\mu+3}} + \frac{\xi z^r \bar{u}(x)}{x^{\mu+4}} \right\} \end{aligned} \quad (G-47a)$$

The footprint  $[f(x, 0, z)]$  is a bell-shape function along  $x$ , with the maximum found at  $x_{max}$ , which follows that:

$$\left. \frac{df(x, 0, z)}{dx} \right|_{x=x_{max}} = 0 \quad (G-47b)$$

To satisfy this equation, the term inside curly bracket in (G-47a) must be zero, or:

$$\left[ \frac{1}{x^{\mu+2}} \frac{d\bar{u}(x)}{dx} - \frac{(\mu+2)\bar{u}(x)}{x^{\mu+3}} + \frac{\xi z^r \bar{u}(x)}{x^{\mu+4}} \right]_{x=x_{max}} = 0 \quad (G-47c)$$

Using (G-41b), the derivative term is expressed as:

$$\frac{d\bar{u}(x)}{dx} = U \frac{m\Gamma(\mu)}{r\Gamma\left(\frac{1}{r}\right)} \left( \frac{\kappa r^2}{U} \right)^{\frac{m}{r}} x^{\frac{m}{r}-1} \quad (G-47d)$$

Substituting this equation along with (G-41b) into (G-47c) leads to:

$$\left[ \frac{m x^{\frac{m}{r}-1}}{r x^{\mu+2}} - \frac{(\mu+2) x^{\frac{m}{r}}}{x^{\mu+3}} + \frac{\xi z^r x^{\frac{m}{r}}}{x^{\mu+4}} \right]_{x=x_{max}} = 0 \quad (G-47e)$$

Because  $x \neq 0$ , it can be simplified as:

$$\left[ mx - r(\mu + 2)x + r\xi z^r \right]_{x=x_{\max}} = 0 \quad (\text{G-47f})$$

The solution of this equation is the location of source/sink that contributes most to the measured flux and is given as:

$$x_{\max} = \frac{r\xi z^r}{2r+1} \quad (\text{G-48})$$

For practical purposes of handling the computation required for the numerical integration, we use  $x_{\max}$  from the 2D footprint approach, although, admittedly, in some cases the solution from the 3D footprint may be preferable since the 3D footprint uses the detailed descriptive dispersion [see page 215 in Kormann and Meixner (2001)].

Upwind range within which the sources/sinks contribute 10 or 90 percent to measured flux. According to (G-41), the percentage of contribution to the measured flux from the upwind range of  $x_p$ , where subscript p indicates percent of 0 to 100, and can be expressed as:

$$p_F(x_p) = 100 \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \lim_{\Delta x \rightarrow 0} \int_{0+\Delta x}^{x_p} \frac{1}{x^{\mu+1}} \exp\left(-\xi \frac{z^r}{x}\right) dx \quad (\text{G-49})$$

This is an increasing monotonic function of  $x_p$ ; therefore, for a given value of  $p_F(x_p)$ , there is a unique value of  $x_p$  that can be found. Similar to the method described for applying the Kljun et al (2004) model, the value of  $x_p$  may be estimated by performing a numerical integration for intervals of  $x$  and then interpolating values of  $P_F(x_p)$  to find the corresponding value of  $x_p$  for  $p_F(x_p) = p$  where  $p = 40, 55$ , or  $90$ .

### G.3.4 Programmatic Approach

#### Calculate the individual variables

Find the exponent of vertical profile of eddy diffusivity [see (G-65) Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19)]:

$$n = \begin{cases} \frac{1}{1 + 5z/L} & z/L > 0 \\ \frac{1 - 24z/L}{1 - 16z/L} & z/L \leq 0 \end{cases} \quad (\text{G-50})$$

Find the exponent of vertical profile of horizontal wind [see (G-76) Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19)]:

$$m = \frac{u_*}{k\sqrt{\bar{u}^2(z) + \bar{v}^2(z)}} \phi_m\left(\frac{z}{L}\right) \quad (\text{G-51})$$

where  $\phi_m(z/L)$  is wind shear, given by:

$$\phi_m\left(\frac{z}{L}\right) = \begin{cases} 1 + 5z/L & z/L > 0 \\ (1 - 16z/L)^{-\frac{1}{4}} & z/L \leq 0 \end{cases} \quad (\text{G-52})$$

Find the wind constant [see (G-74) in Appendix G.4, *Derivation of Analytical Footprint in Kormann and Meixner (2001)* (p. G-19)]

$$U = \frac{\sqrt{u^2(z) + v^2(z)}}{z^m} \quad (\text{G-53})$$

### Composite variables

Calculate the shape factor and other composite variables:

$$r = 2 + m - n \quad (\text{G-54})$$

$\mu$ :

$$\mu = \frac{m+1}{r} \quad (\text{G-55})$$

$\xi$ :

$$\xi = \frac{U}{\kappa r^2} \quad (\text{G-56})$$

Calculate the gamma function of  $\mu$  [see Nemes (2010), verified as accurate]

$$\Gamma(\mu) \approx \sqrt{\frac{2\pi}{\mu}} \left[ \frac{1}{e} \left( \mu + \frac{1}{12\mu - \frac{1}{10\mu}} \right) \right]^\mu \quad (\text{G-57})$$

### Footprint characteristics

Percent of measured scalar flux from upwind range of interest to measurements:

$$p_F(R) = 100 \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \lim_{\Delta x \rightarrow 0} \int_{0+\Delta x}^R \frac{1}{x^{\mu+1}} \exp\left(-\xi \frac{z^r}{x}\right) dx \quad (\text{G-58})$$

Similar to the description of applying the Kljun et al (2004) model, the integral is evaluated by the data logger using four integration segments, each containing scaled integration intervals so as to increase resolution when the slope of the function is changing more and decrease computation when the slope is changing less. The segment boundaries and interval sizes are the same as

described previously, except that when applying the Kormann and Mexiner (2001) model, zero instead of  $R_{kf}$  is used as the first segment's lower boundary.

Location of source/sink that contributes most to the measured flux:

$$x_{\max} = \frac{\xi z^r}{\mu + 1} \quad (\text{G-59})$$

Upwind inflection location of footprint, where the Kormann and Meixner (2001) model is a bell-shaped function, there is one maximum point (turning point) and two inflection points. As described previously, these points should be used as boundaries for the numerical integration segments. One of the inflection points ( $x_{IL}$ ) is located at the left side of the maximum point and given by:

$$x_{IL} = x_{\max} \left( 1 - \frac{1}{\sqrt{\mu + 2}} \right)$$

and the other is at the right side ( $x_{IR}$ ) and given by:

$$x_{IR} = x_{\max} \left( 1 + \frac{1}{\sqrt{\mu + 2}} \right)$$

See the derivation of these inflection points in Appendix G.5, *Upwind Locations at Inflection Points of Footprint in Kormann and Meixner (2001)* (p. G-28).

Upwind range within which the sources/sinks contributes a given percent to measured flux:

$$p = 100 \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \lim_{\Delta x \rightarrow 0} \int_{0+\Delta x}^{x_p} \frac{1}{x^{\mu+1}} \exp\left(-\xi \frac{z^r}{x}\right) dx \quad (\text{G-60})$$

Because an analytical solution for  $x_p$  is not available, the value of  $x_p$  can be interpolated in the process of numerical integration of (G-58) when  $p$  is between two consecutive integrated values. In this way,  $x_{40}$ ,  $x_{55}$ , and  $x_{90}$  are found.

## G.4 Derivation of Analytical Footprint in Kormann and Meixner (2001)

### G.4.1 Model Derivation

Following Horst and Weil (1992), the probability distribution of a scalar concentration downwind of a sink/source in three dimensions may be described using a function  $c(x, y, z)$ , where  $x$  and  $y$  are horizontal spatial variables with  $x$ -axis following mean wind direction, and  $z$  is a vertical spatial variable. The function is approximated using two independent probability distributions of downwind scalar concentration in two dimensions and the vertical profile of horizontal wind speed  $[u(z)]$ , given by:

$$c(x, y, z) = \frac{c(x, y)c(x, z)}{\int_0^\infty u(z)c(x, z)dz} = \frac{c(x, y)c(x, z)}{\bar{u}(x)} \quad (\text{G-61})$$

where  $\bar{u}(x)$  is termed as a plume effective velocity. In probability theory, integration of  $c(x, y, z)$  over the entire domain of  $y$  is the marginal (cross-wind integrated) probability distribution of the downwind scalar concentration in  $x$  and  $z$  [ $c_y(x, z)$ ]. Applying this integration to both sides of (G-61) generates:

$$c_y(x, z) = \frac{c(x, z)}{\bar{u}(x)} \quad (\text{G-62})$$

According to K-theory, the product of the vertical profile of eddy diffusivity [ $K(z)$ ] and the vertical scalar concentration gradient is the scalar flux. Therefore, the cross-wind integrated footprint [ $f_y(x, z)$ ], i.e. the cross-wind integrated probability distribution of flux] is given as:

$$f_y(x, z) = -K(z) \frac{dc_y(x, z)}{dz} \quad (\text{G-63})$$

To analytically express  $f_y(x, z)$  for real-world applications,  $K(z)$  and  $c_y(x, z)$  must be analytically expressed in terms of measured variables.

#### G.4.2 Analytical expression: Vertical profile of eddy diffusivity

The vertical profile of eddy diffusivity can be described as:

$$K(z) = kz^n \quad (\text{G-64})$$

where  $k$  is the von Karman constant (0.41), and  $n$  is the power exponent depending on the surface layer stability, given by (Huang 1979):

$$n = \frac{z}{K(z)} \frac{dK(z)}{dz} = \begin{cases} \frac{1}{1 + 5z/L} & z/L > 0 \\ \frac{1 - 24z/L}{1 - 16z/L} & z/L \leq 0 \end{cases} \quad (\text{G-65})$$

Equations (G-64) and (G-65) express the vertical profile of eddy diffusivity in terms of measured variables.

### G.4.3 Analytical expression: Crosswind integrated scalar concentration distribution

The most common analytic expression for the cross-wind integrated scalar concentration distribution  $[c_y(x, z)]$  is a Gaussian plume model (van Ulden 1978, Horst and Weil 1992), given by:

$$c_y(x, z) = \frac{A}{\bar{u}(x)\bar{z}(x)} \exp\left[-\left(\frac{Bz}{\bar{z}(x)}\right)^r\right] \quad (\text{G-66})$$

where  $A$ ,  $B$ , and  $r$  are parameters.  $\bar{u}(x)$  is the effective speed of plume advection along the streamwise wind vector, implicitly defined in (G-61), given explicitly by:

$$\bar{u}(x) = \frac{\int_0^\infty u(z) c_y(x, z) dz}{\int_0^\infty c_y(x, z) dz} \quad (\text{G-67})$$

and  $\bar{z}(x)$  is the effective height of plume advection along the wind stream, defined by:

$$\bar{z}(x) = \frac{\int_0^\infty z c_y(x, z) dz}{\int_0^\infty c_y(x, z) dz} \quad (\text{G-68})$$

The remaining work is to find parameters of  $A$ ,  $B$ , and  $r$ , and analytically express  $\bar{u}(x)$  and  $\bar{z}(x)$  in terms of measured variables.

#### Parameter estimation: $A$ and $B$

Examination of equation (G-62) reveals that because  $c(x, z)$  is the probability distribution of scalar concentration in two dimensions, we effectively have:

$$\int_0^\infty c_y(x, z) dz = \frac{1}{\bar{u}(x)} \quad (\text{G-69})$$

which means:

$$A = \frac{\bar{z}(x)}{\int_0^\infty \exp\left[-\left(\frac{Bz}{\bar{z}(x)}\right)^r\right] dz} = \frac{B}{\int_0^\infty \exp\left[-\left(\frac{Bz}{\bar{z}(x)}\right)^r\right] d\left(\frac{Bz}{\bar{z}(x)}\right)} = \frac{B}{\frac{1}{r} \Gamma\left(\frac{1}{r}\right)} \quad (\text{G-70})$$

The solution to parameter  $B$  is needed. Submitting (G-66) into (G-68) generates:

$$\bar{z}(x) = \frac{\int_0^\infty z \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] d \left( \frac{Bz}{\bar{z}(x)} \right)}{\int_0^\infty \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] d \left( \frac{Bz}{\bar{z}(x)} \right)} \quad (\text{G-71})$$

Multiplying  $B / \bar{z}(x)$  to both sides of this equation leads to:

$$B = \frac{\int_0^\infty \frac{Bz}{\bar{z}(x)} \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] d \left( \frac{Bz}{\bar{z}(x)} \right)}{\int_0^\infty \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] d \left( \frac{Bz}{\bar{z}(x)} \right)} = \frac{\Gamma \left( \frac{2}{r} \right)}{\Gamma \left( \frac{1}{r} \right)} \quad (\text{G-72})$$

Equations (G-70) and (G-72) give:

$$A = \frac{r \Gamma(2/r)}{[\Gamma(1/r)]^2} \quad (\text{G-73})$$

$$B = \frac{\Gamma(2/r)}{\Gamma(1/r)}$$

**Parameter estimation:  $r$**

This parameter is a shape factor of the plume, given by van Ulden (1978):

$$r = 2 + m - n \quad (\text{G-74})$$

where  $n$  is the power exponent of the vertical profile of eddy diffusivity [see (G-64) and (G-65)], and  $m$  is the exponent of the vertical profile of horizontal wind, given by:

$$u(z) = Uz^m \quad (\text{G-75})$$

which depends on the surface layer stability, given by [page 16, Kaimal and Finnigan (1994)]:

$$m = \frac{z}{u(z)} \frac{du(z)}{dz} = \frac{u_*}{ku(z)} \phi_m \left( \frac{z}{L} \right) \quad (\text{G-76})$$

where  $\phi_m(z/L)$  is wind shear and given by:

$$\phi_m\left(\frac{z}{L}\right) = \begin{cases} 1 + 5z/L & z/L > 0 \\ (1 - 16z/L)^{-1/4} & z/L \leq 0 \end{cases} \quad (\text{G-77})$$

The other parameter  $U$  in (G-75) is a wind constant and can be calculated using measured  $\bar{u}(z)$  and calculated  $m$ :

$$U = \frac{u(z)}{z^m} = \frac{\sqrt{\bar{u}_x(z) + \bar{u}_y(z)}}{z^m} \quad (\text{G-78})$$

**Analytical expression: Effective height of plume advection [ $\bar{z}(x)$ ]**

Examining (G-71) reveals that the numerator can be analytically evaluated only if the term  $B/\bar{z}(x)$  is multiplied to both sides of the equation. As a result, it becomes a Gamma function; therefore, the effective speed of plume advection cannot be analytically expressed in terms of measured variables using its definition in (G-68). Alternatively, differentiating both sides of (G-68) with respect to  $x$  generates:

$$\begin{aligned} \frac{d\bar{z}(x)}{dx} &= \frac{\int_0^\infty z \frac{\partial c_y(x, z)}{\partial x} dz}{\int_0^\infty c_y(x, z) dz} - \frac{\int_0^\infty z c_y(x, z) dz}{\int_0^\infty c_y(x, z) dz} \frac{\int_0^\infty \frac{\partial c_y(x, z)}{\partial x} dz}{\int_0^\infty c_y(x, z) dz} \\ &= \frac{\int_0^\infty [z - \bar{z}(x)] \frac{\partial c_y(x, z)}{\partial x} dz}{\int_0^\infty c_y(x, z) dz} \end{aligned} \quad (\text{G-79})$$

Neglecting the streamwise eddy diffusion, the change in concentration along the wind direction (derivative term) must cause a change in flux due to the continuity in air mass (van Ulden 1978, Horst and Weil 1992), given by:

$$u(z) \frac{\partial c_y(x, z)}{\partial x} = - \frac{\partial}{\partial z} \left[ -K(z) \frac{\partial c_y(x, z)}{\partial z} \right] \quad (\text{G-80})$$

Submitting (G-64) and (G-75) into this equation generates:

$$\frac{\partial c_y(x, z)}{\partial x} = \frac{k}{U} z^{-m} \frac{\partial}{\partial z} \left[ z^n \frac{\partial c_y(x, z)}{\partial z} \right] \quad (\text{G-81})$$



Submitting this equation into (G-79) generates:

$$\frac{d\bar{z}(x)}{dx} = \frac{k}{U} \frac{1}{\int_0^\infty c_y(x, z) dz} \left[ \int_0^\infty z^{1-m} \frac{\partial}{\partial z} z^n \frac{\partial c_y(x, z)}{\partial z} dz - \bar{z}(x) \int_0^\infty z^{-m} \frac{\partial}{\partial z} z^n \frac{\partial c_y(x, z)}{\partial z} dz \right] \quad (G-82)$$

The equation can then be evaluated by substituting (G-66) into the three integration terms on the right-hand side. Performing these three substitutions at once becomes overly complex, so substitution and simplification of each integral term is presented separately here:

#### Integration term in the denominator

$$\int_0^\infty c_y(x, z) dz = \frac{A}{\bar{z}(x) \bar{u}(x)} \int_0^\infty \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] dz = \frac{A}{Br \bar{u}(x)} \Gamma \left( \frac{1}{r} \right) \quad (G-83)$$

#### The first integration term in the numerator

Assuming that the gradient of scalar concentration at the surface ( $z = 0$ ) and beyond the top of boundary-layer ( $z \rightarrow \infty$ ) is zero and the concentration beyond the top of boundary-layer is zero, this integration can be evaluated as follows:

$$\begin{aligned} \int_0^\infty z^{1-m} \frac{\partial}{\partial z} z^n \frac{\partial c_y(x, z)}{\partial z} dz &= z^{1-m+n} \frac{\partial c_y(x, z)}{\partial z} \Big|_0^\infty - \int_0^\infty z^n \frac{\partial c_y(x, z)}{\partial z} d z^{1-m} \\ &= -(1-m) \left[ z^{n-m} c_y(x, z) \Big|_0^\infty - \int_0^\infty c_y(x, z) dz^{n-m} \right] \\ &= (1-m)(n-m) \int_0^\infty z^{n-m-1} \frac{A}{\bar{z}(x) \bar{u}(x)} \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] dz \\ &= \frac{A(1-m)(n-m) \bar{z}^{n-m-1}(x)}{B^{n-m} \bar{u}(x)} \int_0^\infty \left( \frac{Bz}{\bar{z}(x)} \right)^{n-m-1} \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] d \left( \frac{Bz}{\bar{z}(x)} \right) \\ &= \frac{A(1-m)(n-m) \bar{z}^{n-m-1}(x)}{r B^{n-m} \bar{u}(x)} \Gamma \left( \frac{n-m}{r} \right) \\ &= \frac{A(1-m) \bar{z}^{n-m-1}(x)}{B^{n-m} \bar{u}(x)} \Gamma \left( \frac{2}{r} \right) \end{aligned} \quad (G-84)$$

### The second integration term in the numerator

Using the same derivation approach, the second integration terms in the numerator can be evaluated as:

$$\begin{aligned}
 \int_0^\infty z^{-m} \frac{\partial}{\partial z} z^n \frac{\partial c_y(x, z)}{\partial z} dz &= z^{-m+n} \frac{\partial c_y(x, z)}{\partial z} \Big|_0^\infty - \int_0^\infty z^n \frac{\partial c_y(x, z)}{\partial z} d z^{-m} \\
 &= m \left[ z^{n-m-1} c_y(x, z) \Big|_0^\infty - \int_0^\infty c_y(x, z) dz^{n-m-1} \right] \\
 &= -m(n-m-1) \int_0^\infty z^{n-m-2} \frac{A}{\bar{z}(x) \bar{u}(x)} \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] dz \\
 &= - \frac{Am(n-m-1) \bar{z}^{n-m-2}(x)}{B^{n-m-1} \bar{u}(x)} \int_0^\infty \left( \frac{Bz}{\bar{z}(x)} \right)^{n-m-2} \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] d \left( \frac{Bz}{\bar{z}(x)} \right) \\
 &= - \frac{Am(n-m-1) \bar{z}^{n-m-2}(x)}{r B^{n-m-1} \bar{u}(x)} \Gamma \left( \frac{n-m-1}{r} \right) \\
 &= - \frac{Am \bar{z}^{n-m-2}(x)}{B^{n-m} \bar{u}(x)} B \Gamma \left( \frac{1}{r} \right) \\
 &= - \frac{Am \bar{z}^{n-m-2}(x)}{B^{n-m} \bar{u}(x)} \Gamma \left( \frac{2}{r} \right)
 \end{aligned} \tag{G-85}$$

Substituting the evaluated terms in (G-83), (G-84), and (G-85) into (G-82) expresses the derivative of the effective height with respect to  $x$  as a fundamental differential equation:

$$\begin{aligned}
 \frac{d\bar{z}(x)}{dx} &= \frac{\kappa}{U} \frac{1}{\frac{A}{Br\bar{u}(x)} \Gamma\left(\frac{1}{r}\right)} \left\{ \frac{A(1-m)\bar{z}^{n-m-1}(x)}{B^{n-m}\bar{u}(x)} \Gamma\left(\frac{2}{r}\right) - \bar{z}(x) \left[ -\frac{Am\bar{z}^{n-m-2}(x)}{B^{n-m}\bar{u}(x)} \Gamma\left(\frac{2}{r}\right) \right] \right\} \\
 &= \frac{\kappa}{U} rB \frac{\Gamma\left(\frac{2}{r}\right)}{\Gamma\left(\frac{1}{r}\right)} \frac{\bar{z}^{n-m-1}(x)}{B^{n-m}} \\
 &= \frac{\kappa}{U} rB^2 \frac{\bar{z}^{n-m-1}(x)}{B^{n-m}} \\
 &= \frac{\kappa}{U} rB^{2+m-n} \bar{z}^{1-(2+m-n)}(x) \\
 &= \frac{\kappa}{U} rB^r \bar{z}^{1-r}(x)
 \end{aligned} \tag{G-86}$$

This fundamental equation can be written as:

$$\int r\bar{z}^{r-1}(x) d\bar{z}(x) = \frac{\kappa}{U} r^2 B^r \int dx \tag{G-87}$$

therefore:

$$\bar{z}(x) = B \left( \frac{\kappa r^2}{U} x \right)^{\frac{1}{r}} \tag{G-88}$$

**Analytical expression: Effective speed of plume advection  $[\bar{u}(x)]$**

Substituting (G-74) into (G-66) gives:

$$\bar{u}(x) = \frac{U \int_0^\infty z^m c_y(x, z) dz}{\int_0^\infty c_y(x, z) dz} \tag{G-89}$$

The denominator was evaluated in (G-83) and the integration term in the numerator can be evaluated as:

$$\begin{aligned}
 \int_0^\infty z^m c_y(x, z) dz &= \int_0^\infty z^m \frac{A}{\bar{z}(x) \bar{u}(x)} \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] dz \\
 &= \frac{A \bar{z}^m(x)}{B^{m+1} \bar{u}(x)} \int_0^\infty \left( \frac{Bz}{\bar{z}(x)} \right)^m \exp \left[ - \left( \frac{Bz}{\bar{z}(x)} \right)^r \right] d \left( \frac{Bz}{\bar{z}(x)} \right) \quad (G-90) \\
 &= \frac{A \bar{z}^m(x)}{r B^{n-m} \bar{u}(x)} \Gamma \left( \frac{m+1}{r} \right)
 \end{aligned}$$

Substituting this equation along with (G-83) into (G-89) generates:

$$\bar{u}(x) = \frac{U \frac{A \bar{z}^m(x)}{r B^{m+1} \bar{u}(x)} \Gamma \left( \frac{m+1}{r} \right)}{\frac{A}{r B \bar{u}(x)} \Gamma \left( \frac{1}{r} \right)} = U \frac{\bar{z}^m(x)}{B^m} \frac{\Gamma \left( \frac{m+1}{r} \right)}{\Gamma \left( \frac{1}{r} \right)} \quad (G-91)$$

Substituting the analytical expression of effective height of plume advection  $[\bar{z}(x)]$  into this equation generates:

$$\bar{u}(x) = U \frac{\Gamma \left( \frac{m+1}{r} \right)}{\Gamma \left( \frac{1}{r} \right)} \left( \frac{\kappa r^2}{U} x \right)^{\frac{m}{r}} \quad (G-92)$$

By substituting the solved parameters of  $A$  and  $B$  (G-73), analytically expressed effective height of plume advection  $[\bar{u}(x)]$ , see (G-88), and analytical expressed effective speed of plume advection  $[\bar{z}(x)]$ , see (G-92) into (G-66), finally, the cross-wind integrated scalar concentration distribution can be analytically expressed in terms of spatial variables ( $x$  and  $z$ ), the constant in the power-law profile of the eddy diffusivity ( $\kappa$ ), and calculated variables from measurements ( $m$ ,  $n$ , and  $U$ ).

That is:

$$c_y(x, z) = \frac{r \frac{\Gamma(2/r)}{\Gamma^2(1/r)}}{U \frac{\Gamma[(m+1)/r]}{\Gamma(1/r)} \left( \frac{\kappa r^2}{U} x \right)^{\frac{m}{r}} B \left( \frac{\kappa r^2}{U} x \right)^{\frac{1}{r}}} \exp \left[ - \left( \frac{Bz}{B \left( \frac{\kappa r^2}{U} x \right)^{\frac{1}{r}}} \right)^r \right] \quad (\text{G-93})$$

$$= \frac{r}{U \Gamma[(m+1)/r]} \left( \frac{U}{\kappa r^2 x} \right)^{\frac{m+1}{r}} \exp \left[ - \frac{U z^r}{\kappa r^2 x} \right]$$

More succinctly, given that:

$$\xi = \frac{U}{\kappa r^2} \quad (\text{G-94})$$

$$\mu = \frac{m+1}{r}$$

the cross-wind integrated scalar concentration distribution, in an analytical form, can be presented as:

$$c_y(x, z) = \frac{r}{U \Gamma(\mu)} \left( \xi \frac{1}{x} \right)^\mu \exp \left[ - \xi \frac{z^r}{x} \right]$$

Examining equation (G-62) reveals that the cross-wind integrated footprint can be thus derived as:

$$\begin{aligned} f_y(x, z) &= -K(z) \frac{dc_y(x, z)}{dz} \\ &= -\kappa z^n \frac{r}{U \Gamma(\mu)} \left( \xi \frac{1}{x} \right)^\mu \exp \left( - \xi \frac{z^r}{x} \right) \left( - \xi \frac{r z^{r-1}}{x} \right) \quad (\text{G-95}) \\ &= \frac{1}{\Gamma(\mu)} \xi^\mu \left( \frac{z^{m+1}}{x^{\mu+1}} \right) \exp \left( - \xi \frac{z^r}{x} \right) \end{aligned}$$

## G.5 Upwind Locations at Inflection Points of Footprint in Kormann and Meixner (2001)

As described previously, integration segment boundaries should be determined by the upwind inflection points of the footprint. Since the footprint is known to

be a bell-shaped function, there is one maximum point ( $x_{max}$ ) and two inflection points ( $x_{IL}$  and  $x_{IR}$ ) on both sides of the maximum, respectively. Accordingly,  $x_{max}$  may be found by setting the first order derivative of the footprint function to zero. Similarly,  $x_{IL}$  and  $x_{IR}$  may be found by setting the second order derivative to zero. The following section shows derivations for these points.

### G.5.1 Footprint Model

The cross-wind integrated footprint [ $f_y(x, z)$ ] in Kormann and Meixner (2001) is given by:

$$f_y(x, z) = \frac{1}{\Gamma(\mu)} \xi^\mu \left( \frac{z^{m+1}}{x^{\mu+1}} \right) \exp\left(-\xi \frac{z^r}{x}\right) \quad (G-96)$$

where  $x$  is the upwind distance to the measurement station;  $z$  is measurement aerodynamic height;  $m$  is the exponent of the vertical profile of horizontal wind velocity; and  $r$ ,  $\mu$ , and  $\xi$  are composite variables, given by:

**Shape factor:**

$$r = 2 + m - n \quad (G-97)$$

where  $n$  the exponent of vertical profile of eddy diffusivity.

**$\mu$ :**

$$\mu = \frac{m+1}{r} \quad (G-98)$$

**$\xi$ :**

$$\xi = \frac{U}{\kappa r^2} \quad (G-99)$$

where  $U$  is the wind constant.

### G.5.2 Upwind Location of Maximum Footprint

Differentiating (G-96) with respect to  $x$  generates:

$$\frac{df_y(x, z)}{dx} = \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \frac{d}{dx} \left[ \frac{1}{x^{\mu+1}} \exp\left(-\xi \frac{z^r}{x}\right) \right] \quad (G-100)$$

$$= \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \exp\left(-\xi \frac{z^r}{x}\right) \left[ \frac{\xi z^r - x(\mu+1)}{x^{\mu+3}} \right]$$

The marginal streamwise footprint  $[f_y(x, z)]$  is a bell-shape function with respect to  $x$ , with the maximum found at  $x_{max}$ , which follows that:

$$\left. \frac{df_y(x, z)}{dx} \right|_{x=x_{max}} = 0 \quad (G-101)$$

All terms except for the term in the square bracket in (G-100) are greater than zero for any real-world case in the field, and therefore setting that term equal to zero results in the solution for  $x_{max}$ :

$$x_{max} = \frac{\xi z^r}{\mu + 1} \quad (G-102)$$

### G.5.3 Upwind Location of Inflection Points in Footprint Curve

Differentiating both sides of (G-100) with respect to  $x$  generates:

$$\begin{aligned} \frac{d^2 f_y(x, z)}{dx^2} &= \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \frac{d}{dx} \left\{ \exp\left(-\xi \frac{z^r}{x}\right) \left[ \frac{\xi z^r - x(\mu + 1)}{x^{\mu+3}} \right] \right\} \\ &= \frac{\xi^\mu z^{m+1}}{\Gamma(\mu)} \exp\left(-\xi \frac{z^r}{x}\right) \left\{ \xi \frac{z^r}{x^2} \left[ \frac{\xi z^r - x(\mu + 1)}{x^{\mu+3}} \right] - \frac{(\mu + 3)\xi z^r}{x^{\mu+4}} + \frac{(\mu + 1)(\mu + 2)}{x^{\mu+3}} \right\} \end{aligned} \quad (G-103)$$

Because the footprint is a bell-shaped function, it has two inflection points. One is to the left of  $x_{max}$  ( $x_{IL}$ ), and the other is to the right of  $x_{max}$  ( $x_{IR}$ ). Equation (G-103) must equal zero at the inflection points. In this equation, the term ahead of the curly bracket is never zero. Therefore we can simply set the terms in the curly brackets to zero to find the inflection points:

$$\xi \frac{z^r}{x^2} \left[ \frac{\xi z^r - x(\mu + 1)}{x^{\mu+3}} \right] - \frac{(\mu + 3)\xi z^r}{x^{\mu+4}} + \frac{(\mu + 1)(\mu + 2)}{x^{\mu+3}} = 0 \quad (G-104)$$

Rearranging the terms in this equation yields:

$$\xi^2 z^{2r} - 2(\mu + 2)\xi z^r x + (\mu + 1)(\mu + 2)x^2 = 0 \quad (G-105)$$

Solving the quadratic equation results in:

$$x = \frac{\xi z^r (\mu + 2 \pm \sqrt{\mu + 2})}{(\mu + 1)(\mu + 2)} \quad (G-106)$$

Substituting  $x_{\max}$  [see equation (G-102)] into (G-106) and then taking the point to the left results in:

$$x_{IL} = x_{\max} \left( 1 - \frac{1}{\sqrt{\mu + 2}} \right) \quad (\text{G-107})$$

and taking the point to the right gives:

$$x_{IR} = x_{\max} \left( 1 + \frac{1}{\sqrt{\mu + 2}} \right) \quad (\text{G-108})$$

## G.6 References

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# Appendix H. Surface Energy Flux

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Calculation of the soil surface heat flux is done only if all necessary measurements are available, which includes soil heat flux, soil temperature, and soil volumetric water content.

The soil surface heat flux,  $G$ , typically reported in units  $\text{W}\cdot\text{m}^{-2}$ , is found by summing the average soil heat flux measured at some depth and the change in heat storage in the layer of soil above that depth over some interval of time:

$$G = G_{\text{Depth}} + \Delta_{\text{storage}}$$

$G_{\text{Depth}}$  in the program is found by averaging the heat flux measurements from soil heat flux plates over the averaging interval, e.g., 30 minutes. If there are multiple heat flux plates, an average of the temporal averages of each plate is used.

In the data logger program, calculation of the change in storage is done as follows:

$$\Delta_{\text{storage}} = \frac{[c_s \rho_s (T_{\text{soil},f} - T_{\text{soil},i}) + c_w \rho_w (T_{\text{soil},f} q_{v,f} - T_{\text{soil},i} q_{v,i})] D}{\Delta t}$$

where:

$c_s$  = the specific heat of dry mineral soil at the site in  $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ . This value is among the station configuration variables (see  $C_{\text{dry\_soil}}$  in TABLE 4-1) entered by the user. If no value was entered, a default of 870 is used.

$\rho_s$  = the soil bulk density at the site in  $\text{kg}\cdot\text{m}^{-3}$  and is entered by the user (see *Bulk Density* in TABLE 4-1). If no value was entered, a default of 1300 is used.

$T_{\text{soil},f}$  = the soil temperature averaged over the last minute of the current flux averaging interval.

$T_{\text{soil},i}$  = the soil temperature averaged over the last minute of the previous flux averaging interval.

$c_w$  = the specific heat of liquid water in  $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ . A value of 4210 is used, which is the specific heat of liquid water at 0 °C.

$\rho_w$  = the density of liquid water in  $\text{kg}\cdot\text{m}^{-3}$ . A value of 1000 is used.

$q_{v,f}$  = the volumetric water content averaged over the last minute of the current flux averaging interval (e.g., 30 minutes).

$q_{v,i}$  = the volumetric water content averaged over the last minute of the previous flux averaging interval.

$D$  = the depth in m below the surface at which the soil heat flux plates are buried and is entered by the user (see *HFP Depth* in TABLE 4-1). If no value was entered, a default of 0.08 is used.

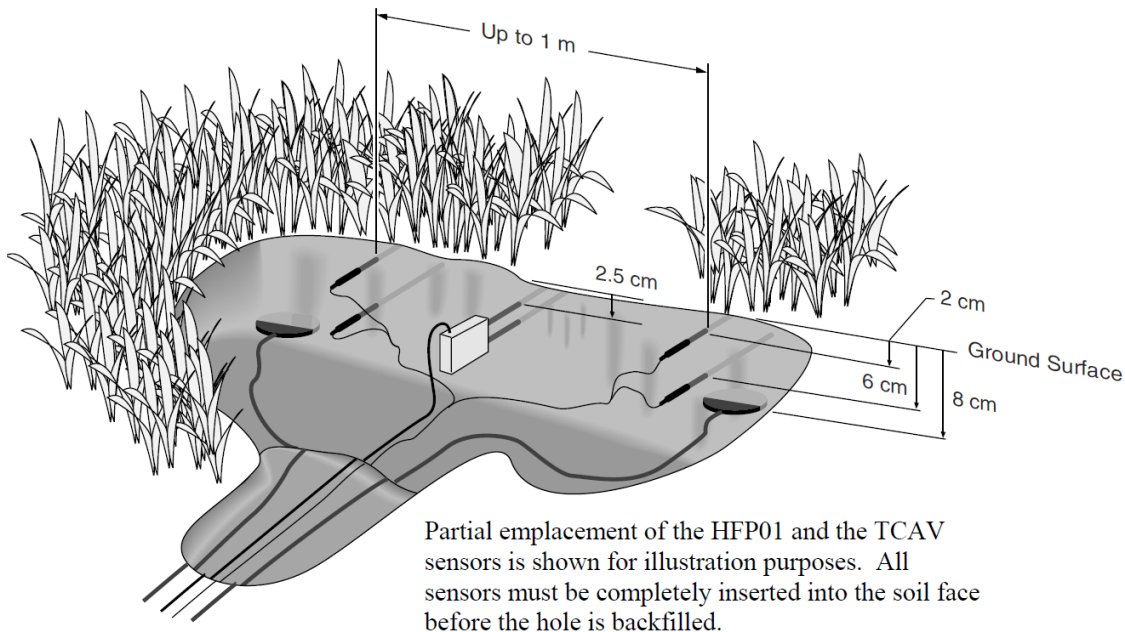
$\Delta t$  = the length of time of the flux averaging interval (e.g., 30 minutes).

**NOTE** TCAV and CS65X sensors both make soil temperature measurements. However, if they are both being used, the TCAV measurements will be used preferentially for  $T_{soil,f}$  and  $T_{soil,i}$ , as the TCAV provides a greater spatial average.

**NOTE** The program supports either CS616s or CS65Xs for measurements of soil water content. It won't support both types of sensors at the same time.

**NOTE** If a CS616 is used, outputs for water content are corrected for temperature as detailed in the CS616 manual. The temperature measurement from the TCAV sensor assumed to be closest to the CS616 is used for this correction.

It is assumed that soil sensors are installed in a manner similar to that presented in the figure below. In many applications, the setup shown in the figure (two heat flux plates, one TCAV, and one CS616) is replicated for better spatial averaging at the site. Accordingly, the program supports up to four soil heat flux plates (HFP01 or HFP01SC), two soil temperature sensors (TCAV or CS65X), and two water content sensors (CS616 or CS65X).



Finally, if a measurement of average net radiation over the flux-averaging interval is available, energy closure may be calculated as follows:

$$E_{closure} = \frac{LE + H}{R_n - G}$$

Where all variables are in  $\text{W}\cdot\text{m}^{-2}$  and LE is latent heat flux, H is sensible heat flux, and  $R_n$  is net radiation.

# ***Appendix I. EasyFlux DL CR60P Process Flow Diagram***

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## **Sequence of Program Functions**

Every SCAN\_INTERVAL (default 100 ms)

Collect raw data from gas analyzer, sonic anemometer, FW (if applicable), and panel temp



Align data, accounting for electronic delays



Parse out diagnostic flags from gas analyzer and sonic data



Calculate various variables (e.g., e, rho\_d, rho\_a, Td, CO2\_mixratio, H2O\_mixratio, RH)



Store raw data in multiple datasets, each dataset with a different lag applied to gas analyzer data relative to sonic data (to be used later in cross correlation; lags from -MAX\_LAG to +MAX\_LAG are used; MAX\_LAG default is 2)



If using FW, store raw data in multiple datasets, each dataset with a different lag applied to FW data relative to sonic data (to be used later in cross correlation; lags from -MAX\_LAG to +MAX\_LAG are used; MAX\_LAG default is 2)



Write a record to ts\_data and diagnostic output tables

Every SLOWSEQUENCE\_SCAN\_INTERVAL (default 5 s)

Measure battery voltage



Measure biomet and energy balance (slow response) sensors



If station variables have changed, save new values to memory

### Every 5 Minutes

Do coordinate rotations and find the 5-minute covariances for u with w, v with w, Ts with w, CO<sub>2</sub> with w, and H<sub>2</sub>O with w (used later for steady state test for quality grading; see Appendix F on Data Quality Grading).

### Every AVERAGING\_INTERVAL (default 30 minutes)

Filter out data with diagnostic flags or signal strengths or measurements outside of acceptable ranges, do coordinate rotations (use double coordinate rotation method unless planar fit angles have been entered by user), and recalculate all covariances with rotated wind components. (See Appendix B on Double Coordinate Rotation and Appendix C on Planar Fit Rotation.)



Use rotated wind components to find turbulent kinetic energy, friction velocity, and preliminary values of Monin-Obukhov length and stability



Calculate frequency correction factors for wTs, wu, and vw to account for block averaging and line averaging. If conditions are stable, iteratively calculate Monin-Obukhov length, cospectral equations, and correction factors until factors change by <0.0001 or until 10 iterations have completed. (See Appendix D on Frequency Corrections.)



Calculate value for steady state test using the 30-minute momentum covariances and the 5-minute momentum covariances. (see Appendix F on Data Quality Grading.)



Calculate the overall quality grade for momentum flux. (See Appendix F on Data Quality Grading.)



Calculate and use a new roughness length if 1) user didn't enter a fixed value, 2) there is neutral stability, and 3) wind speed is >3 m/s. (See Appendix G on Footprint.)



Calculate footprint characteristics using the Kljun et al (2004) model if conditions are appropriate, else use Kormann and Meixner (2001) model. (See Appendix G on Footprint.)



Calculate the covariance of CO<sub>2</sub> and rotated wind components for each lagged dataset.



Find the effective lateral separation distance between gas analyzer and sonic (to use in frequency correction) and the effective separation scan lag (used to constrain which lagged datasets are physically possible). (See Appendix D on Frequency Corrections.)



Find the dataset with the physically possible lag that maximizes the covariance of CO<sub>2</sub> and vertical wind. Use this dataset for the FLUX\_AMERIFLUXFORMAT and FLUX\_CSFORMAT output tables. If any results are invalid, continue with lag of zero. (See Appendix D on Frequency Corrections.)



Assume the same lag found for CO<sub>2</sub> will also maximize covariance of H<sub>2</sub>O and vertical wind. Calculate covariances of appropriately lagged H<sub>2</sub>O and rotated wind components.



Calculate cospectra functions and frequency correction factors for covariances of CO<sub>2</sub> and rotated wind components, taking into account attenuation from block averaging, line averaging, and spatial separation. (See Appendix D on Frequency Corrections.)



Calculate cospectra functions and frequency correction factors for covariances of H<sub>2</sub>O and rotated wind components, taking into account attenuation from block averaging, line averaging, and spatial separation. (See Appendix D on Frequency Corrections.)



Calculate final momentum flux from rotated and frequency corrected covariances of u with w and v with w.



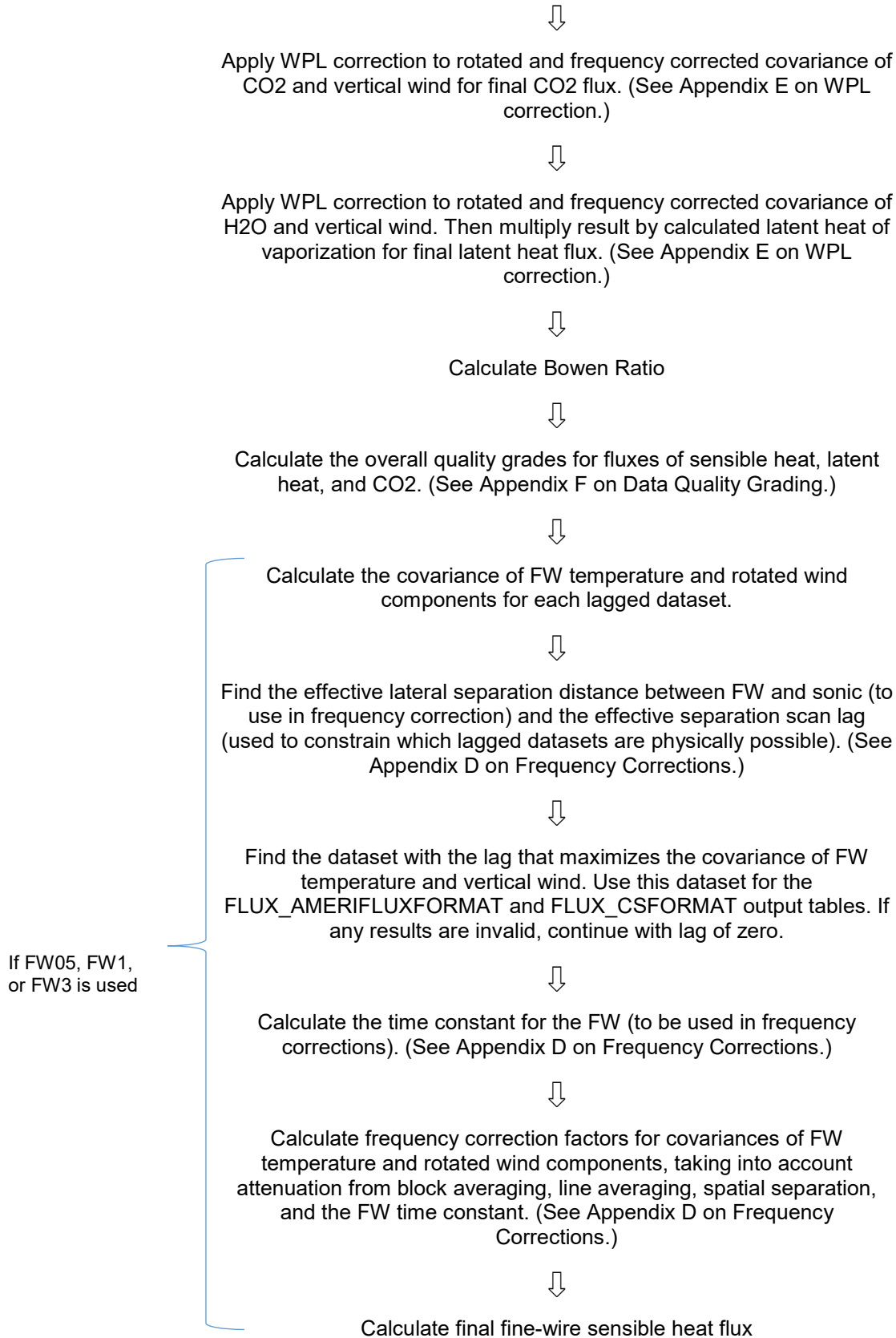
Apply SND correction to the rotated and frequency corrected covariance of w and T<sub>s</sub>.



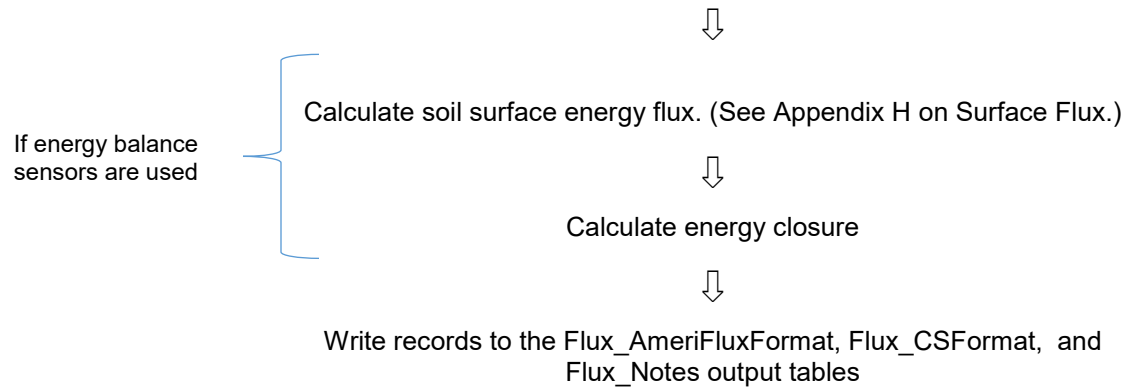
Calculate specific heat of ambient (moist) air and calculate final sensible heat flux.



Calculate scaling temperature (used for data quality grading). (See Appendix F on Data Quality Grading.)



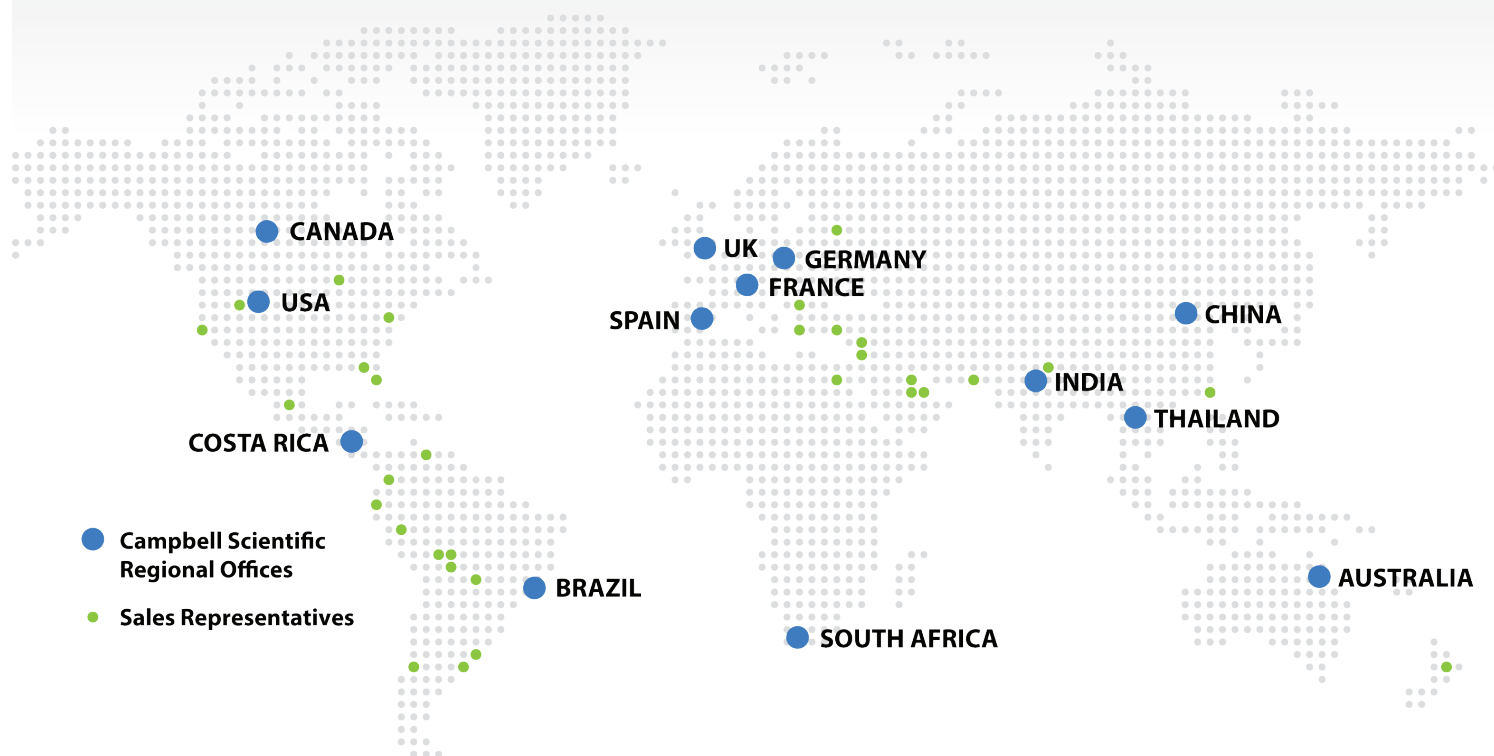






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