BOWEN RATIO INSTRUMENTATION
INSTRUCTION MANUAL

REVISION: 4/98

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CAMPBELL SCIENTIFIC, INC.

815 W. 1800 N.	Campbell Scientific Canada Corp.	Campbell Scientific Ltd.
Logan, UT 84321-1784	11564 -149th Street	Campbell Park
USA	Edmonton, Alberta T5M 1W7	80 Hathern Road
Phone (435) 753-2342	CANADA	Shepshed, Leics. LE12 9RP
FAX (435) 750-9540	Phone (403) 454-2505	ENGLAND
www.campbellsci.com	FAX (403) 454-2655	Phone (44)-50960-1141
		FAX (44)-50960-1091

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SECTION 1. SYSTEM OVERVIEW

1.1 REVIEW OF THEORY

By analogy with molecular diffusion, the flux-gradient approach to vertical transport of an entity from or to a surface assumes steady diffusion of the entity along its mean vertical concentration gradient.

When working within a few meters of the surface, the water vapor and heat flux densities, E and H, may be expressed as:

$$E = k_v \frac{\partial \rho_v}{\partial z} \qquad (1)$$

$$H = \rho C_p k_H \frac{\partial T}{\partial z} \qquad (2)$$

Here ρ_v is vapor density, ρ is air density, C_p is the specific heat of air, T is temperature, z is vertical height, and k_v and k_H are the eddy diffusivities for vapor and heat, respectively. Air density and the specific heat of air should account for the presence of water vapor, however, use of standard dry air values usually causes negligible error. The eddy diffusivities are functions of height. The vapor and temperature gradients reflect temporal and spatial averages.

Applying the Universal Gas Law to Eq. (1), and using the latent heat of vaporization, λ, the latent heat flux density, λ, can be written in terms of vapor pressure (e).

$$L_e = \frac{\lambda \rho \varepsilon k_v}{P} \frac{\partial e}{\partial z} \qquad (3)$$

Here P is atmospheric pressure and ε is the ratio of the molecular weight of water to the molecular weight of dry air.

In practice, finite gradients are measured and an effective eddy diffusivity assumed over the vertical gradient:

$$L_e = \frac{\lambda \rho \varepsilon k_v}{P} \frac{(e_1 - e_2)}{(z_1 - z_2)} \qquad (4)$$

$$H = \rho C_p k_H \frac{(T_1 - T_2)}{(z_1 - z_2)}. \qquad (5)$$

In general, k_v and k_H are not known but under specific conditions are assumed equal. The ratio of H to L_e is then used to partition the available energy at the surface into sensible and latent heat flux. This technique was first proposed by Bowen (1926). The Bowen ratio, β, is obtained from Eq. (4) and Eq. (5).

$$\beta = \frac{H}{L_e} = \frac{PC_p}{\lambda \varepsilon} \frac{(T_1 - T_2)}{(e_1 - e_2)} \qquad (6)$$

where $PC_p / \lambda \varepsilon$ is the psychrometric constant.

The surface energy budget is given by,

$$R_n - G - H - L_e = 0, \qquad (7)$$

where R_n is net radiation for the surface and G is the total soil heat flux. The sign convention used is R_n positive into the surface and G, H, and L_e positive away from the surface. Substituting βL_e for H in Eq. (7) and solving for L_e yields:

$$L_e = \frac{R_n - G}{1 + \beta}. \qquad (8)$$

Measurements of R_n, G, and T and e at two heights are then required to estimate sensible and latent heat flux.

Atmospheric pressure is also necessary, but seldom varies by more than a few percent. It may be calculated for the site elevation, assuming a standard atmosphere, or obtained from a nearby station and corrected for any elevation difference (Wallace and Hobbes, 1977).

Eq. (6) shows that the sensitivity of β is directly related to the measured gradients; a 1% error in a measurement results in a 1% error in β.

When the Bowen ratio approaches -1, the calculated fluxes approach infinity. Fortunately, this situation usually occurs only at night when there is little available energy, R_n - G. In practice, when β is close to -1 (e.g., $-1.25 < \beta < -0.75$), L_e and H are assumed to be negligible and are not calculated. Ohmuna (1982) describes an objective method for rejecting erroneous Bowen ratio data.

WATER VAPOR MEASUREMENT
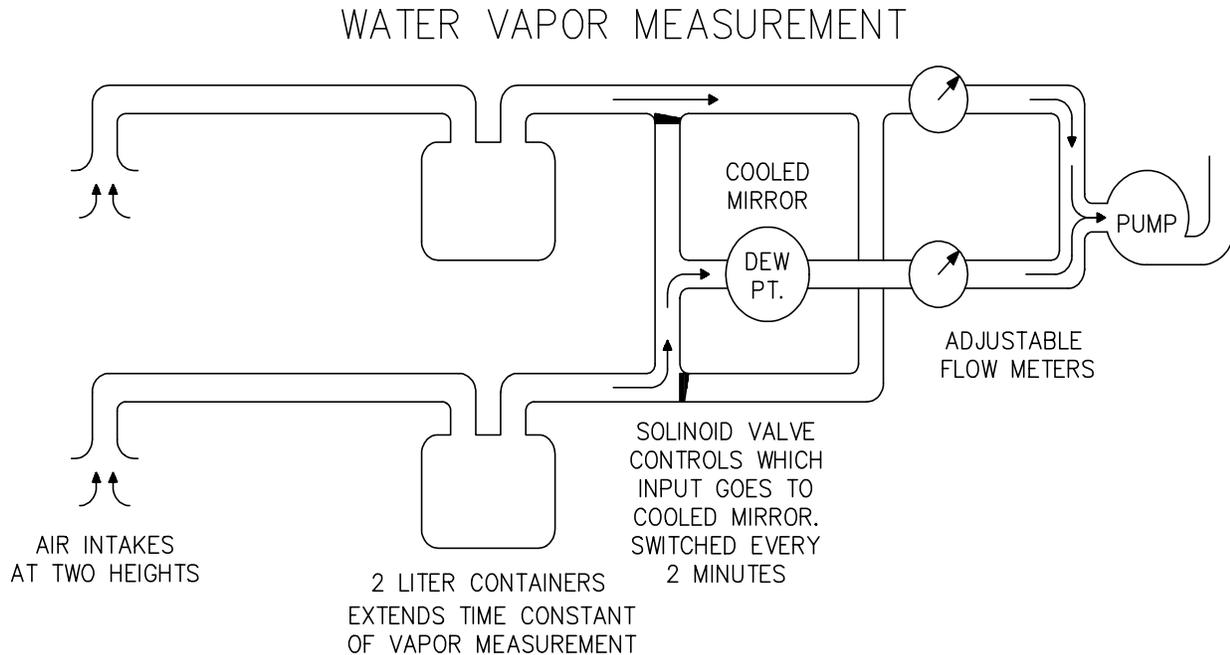
FIGURE 1.2-1 Vapor Measurement System

1.2 SYSTEM DESCRIPTION

1.2.1 WATER VAPOR MEASUREMENT

It is common practice in Bowen ratio measurements to measure wet bulb depression to develop the water vapor gradient. The position of the two psychrometers is periodically reversed to cancel systematic sensor errors (Suomi, 1957; Fuchs and Tanner, 1970).

In the Campbell Scientific system, vapor concentration is measured with a single cooled mirror dew point hygrometer[1], using a technique developed for multiple level gradient studies (Lemon, 1960). Air samples from two heights are routed to the cooled mirror after passing through mixing volumes (Figure 1.2-1). The problems associated with wick wetting and water supply in psychrometers are avoided and systematic sensor errors are eliminated.

Air is drawn from both heights continuously through inverted 25 mm filter holders fitted with Teflon filters with a 1 μm pore size. The filter prevents dust contamination in the lines and on the cooled mirror. It also prevents liquid water from entering the system.

A single low power DC pump aspirates the system. Manually adjustable rotometers are used to adjust and match the flow rates. A flow rate of 0.4 liters/minute with 2 liter mixing chambers gives a 5 minute time constant.

A datalogger is used to measure all sensors and control the valve that switches the air stream through the cooled mirror.

The resolution of the dewpoint temperature measurement is ± 0.003°C over a ± 35°C range. The limitation is the stability of the Dew-10, approximately 0.05°C, yielding better than ± 0.01 kPa vapor pressure resolution over most of the environmental range.

Every 2 minutes the air drawn through the cooled mirror is switched from one height to the other with the valve. Forty seconds is allowed for the mirror to stabilize on the new dewpoint temperature and 1 minute and 20 seconds worth of measurements for an individual level are obtained for each 2 minutes cycle.

The dewpoint temperature is measured every second and the vapor pressure is calculated by the datalogger using the equation described by Lowe (1976). The average vapor pressure at each height is calculated every 20 minutes.

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[1]Model Dew-10, General Eastern Corp. Watertown, MA

TEMPERATURE GRADIENT MEASUREMENT
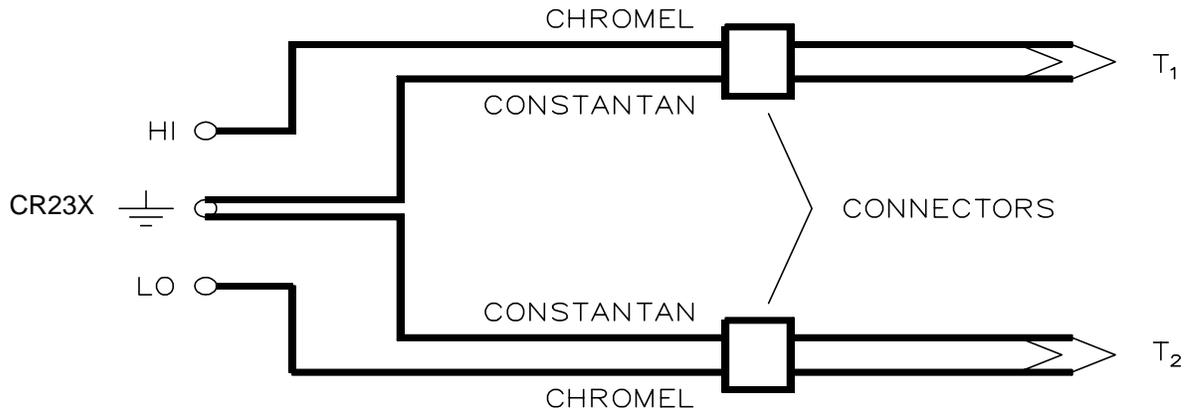
FIGURE 1.2-2. Thermocouple Configuration

1.2.2 AIR TEMPERATURE MEASUREMENT

Air temperature is measured at two heights with chromel–constantan thermocouples wired as in Figure 1.2-2. The differential voltage is due to the difference in temperature between T_1 and T_2 and has no inherent sensor offset error. The datalogger resolution is 0.006°C with 0.1 μV rms noise.

The thermocouples are not aspirated. Attempts to aspirate the TCs with the air from the vapor measurement system were not successful. Testing under 1000 W m^{-2} solar radiation, with several radiation shield designs and aspiration rates of up to 80 cm s^{-1} (1 l min^{-1}), showed a significant increase in temperature due to radiation from the shield/ducting.

Calculations indicate that a 25 μm (0.001 in) diameter TC experiences less than 0.2°C and 0.1°C heating at 0.1 m s^{-1} and 1 m s^{-1} wind speeds, respectively, under 1000 W m^{-2} solar radiation (Tanner, 1979). More importantly, error in the gradient measurement is due only to the difference in the radiative heating of the two TC junctions and their physical symmetry minimizes this. Conversely, contamination of only one junction can cause larger errors.

Applying temperature gradients to the TC connectors was found to cause offsets. The connector mounts were designed with radiation shields and thermal conductors to minimize gradients.

The prototype systems used two sets of TCs on each system, one 25 μm and one 76 μm diameter. It was hypothesized that the 25 μm diameter would suffer less from radiation loading and the 76 μm would be less prone to breakage. The current design uses a single set of TCs (76 μm standard) with two parallel junctions at each height as a back up against breakage.

1.2.3 NET RADIATION AND SOIL HEAT FLUX

Net radiation and soil heat flux are averaged over the same time period as the vapor pressure and temperature differences.

To measure soil heat flux, heat flux plates are buried in the soil at a fixed depth of between 5 to 10 cm to reduce errors due to vapor transport of heat. Typically the plates are buried at a depth of 8 cm. The average temperature of the soil layer above the plate is measured using 4 parallel thermocouples. The heat flux at the surface is then calculated by adding the heat flux measured by the plate to the energy stored in the soil layer. The storage term is calculated by multiplying the change in soil temperature over the averaging period by the soil heat capacity.

1.2.4 POWER SUPPLY

The current requirements of the components of the Bowen ratio system are given in Table 1.2-1.

TABLE 1.2-1 Component Power Requirements	
COMPONENT	CURRENT at 12 VDC
Cooled Mirror	150 - 500 mA
Pump	60 mA
CR23X	5 mA

A 20 watt solar panel (MSX20R) and a 70 amp-hour battery are capable of providing a continuous current of 300 - 350 mA. The solar panel is necessary if the system is to be used for periods longer than 2-3 days. The datalogger can control power to the cooled mirror and pump, and can shut down the system if the battery voltage is low or if measurements are not needed at night.

SECTION 2. STATION INSTALLATION

Figure 2-1 shows the typical Bowen ratio installation on the CM10 tripod. The 023A enclosure, mounting arms, and MSX20R solar panel all mount to the tripod mast (1 1/4 in. pipe, inside diameter) with U-bolts. The size of the tripod allows the heights of the arms to be adjusted from 0.5 to 3 meters. The mounting arms should be oriented due south to avoid partial shading of the thermocouples.

The net radiometer is mounted on a separate stake (not provided by Campbell Scientific) so that the tripod is not a significant portion of its field of view. It should be positioned so that it is never shaded by the tripod or mounting arms and should be mounted so that it points south.

2.1 SENSOR HEIGHT AND SEPARATION

There are several factors which must be balanced against each other when determining the height at which to mount the support arms for the temperature and air intakes. The differences in temperature and moisture increase with height, so the resolution on the measurements of the temperature and vapor gradient will improve the farther apart the arms are.

The upper mounting arm must be low enough that it is not sampling air that is coming from a different environment upwind. The air that the sensors see must be representative of the

soil/vegetation that is being measured. As a rule of thumb, the surface being measured should extend a distance upwind that is **at least** 100 times the height of the sensors. The following references discuss fetch requirements in detail: Brutsaert (1982); Dyer and Pruitt (1962); Gash (1986); Schuepp et al. (1990); and Shuttleworth (1992).

The lower mounting arm needs to be higher than the surrounding vegetation so that the air it is sampling is representative of the bulk crop surface, and not a smaller scale effect that might be seen in a row crop if the sensors were down between rows.
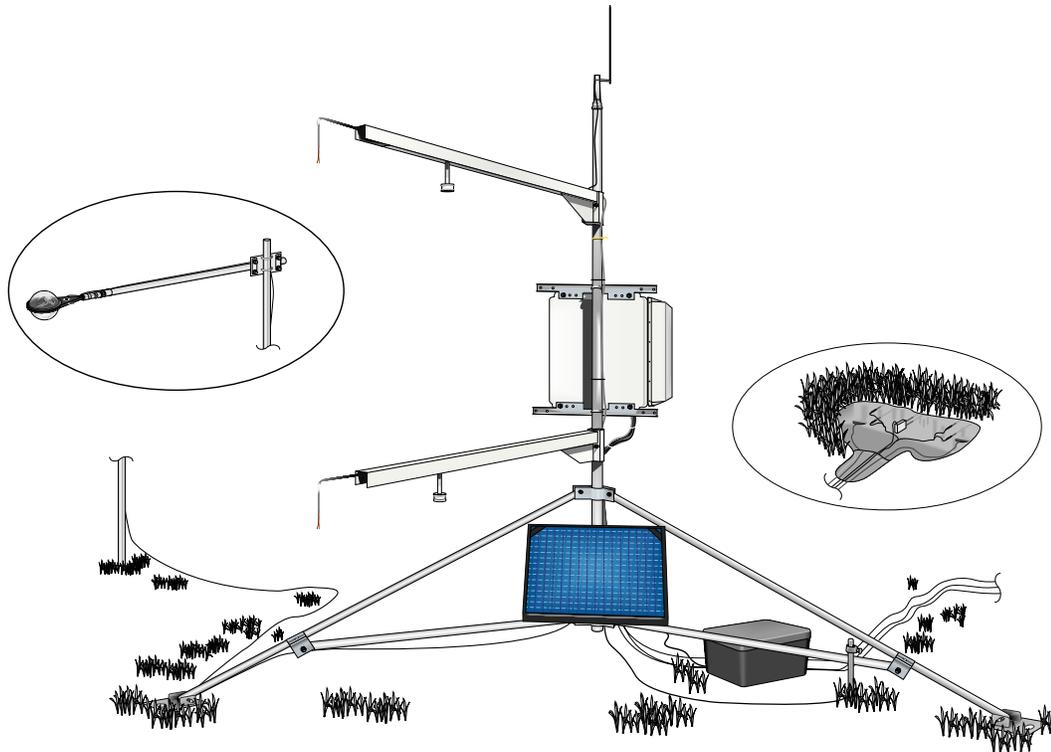
FIGURE 2-1. CSI Bowen Ratio System

2.2 SOIL THERMOCOUPLES AND HEAT FLUX PLATES

The soil thermocouples and heat flux plates are typically installed as shown in Figure 2.2-1. The TCAV parallels four thermocouples together to provide the average temperature, as shown in Figure 2.2-2). It is constructed so two thermocouples can be used to obtain the average temperature of the soil layer above one heat flux plate and the other two above the second plate. The thermocouple pairs may be up to two meters apart.

The location of the two heat flux plates/ thermocouples should be chosen to be representative of the area under study. If the ground cover is extremely varied, it may be necessary to have additional sensors to provide a valid average.

Use a shovel to cut a vertical slice in the soil and remove the soil to one side of the cut. Try to keep the soil that is removed intact so that it can be replaced with as little disruption as possible.

The sensors are installed in the undisturbed face. The depths are measured from the top of the soil. A horizontal cut is made with a knife to install the heat flux plate, and the stainless steel tubes on the ends of the thermocouple are pressed in, keeping the tubes horizontal. When removing the thermocouples, grip the tubing, not the thermocouple wire.

To minimize thermal conduction down the sensor lead wires, they should be buried for a short distance back from the sensor. In particular, do not run the leads directly to the surface, but wrap them around the edge of the hole, keeping the leads at the same level as the sensor for as long as possible. Once the sensors are installed, backfill the hole.

Install the CS615 as shown in Figure 2.2-1. See the CS615 manual (Section 5) for detailed installation instructions.
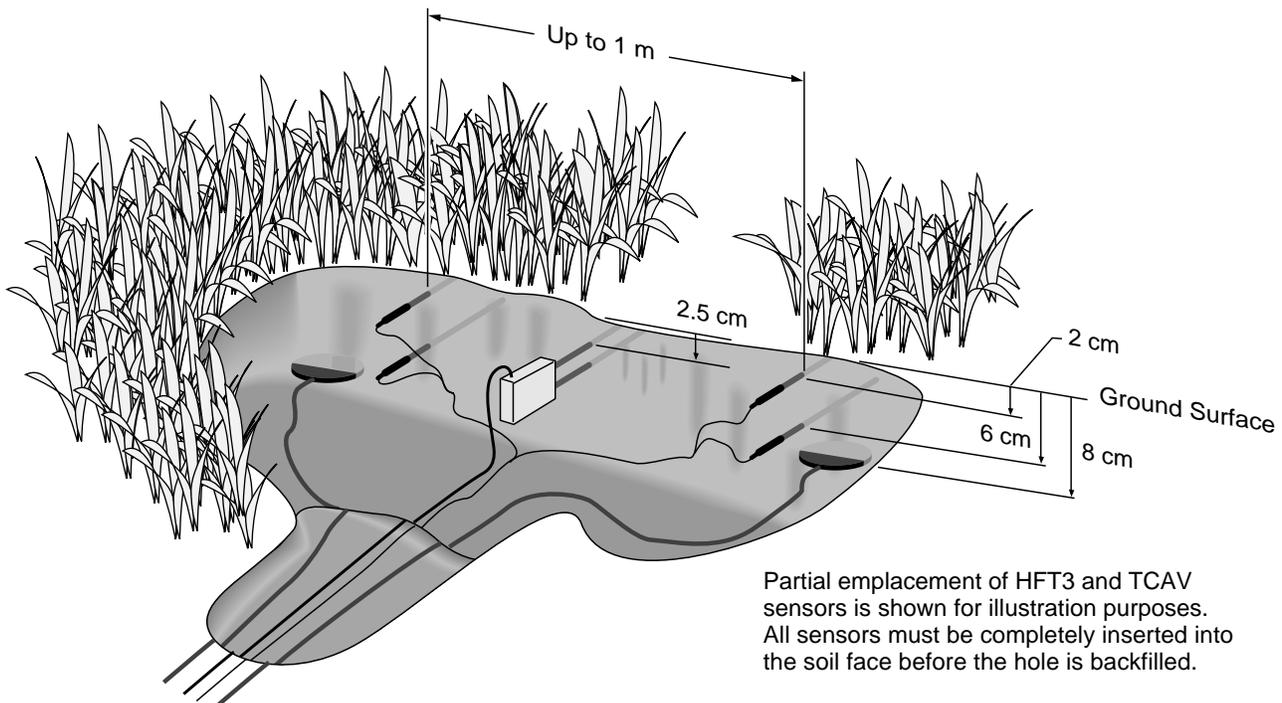
FIGURE 2.2-1. Placement of Thermocouples and Heat Flux Plates

24 GAUGE
CHROMEL
CONSTANTAN

HI (PURPLE)

LO (RED)

40 GAUGE CHROMEL
CONSTANTAN

STAINLESS
STEEL TUBE
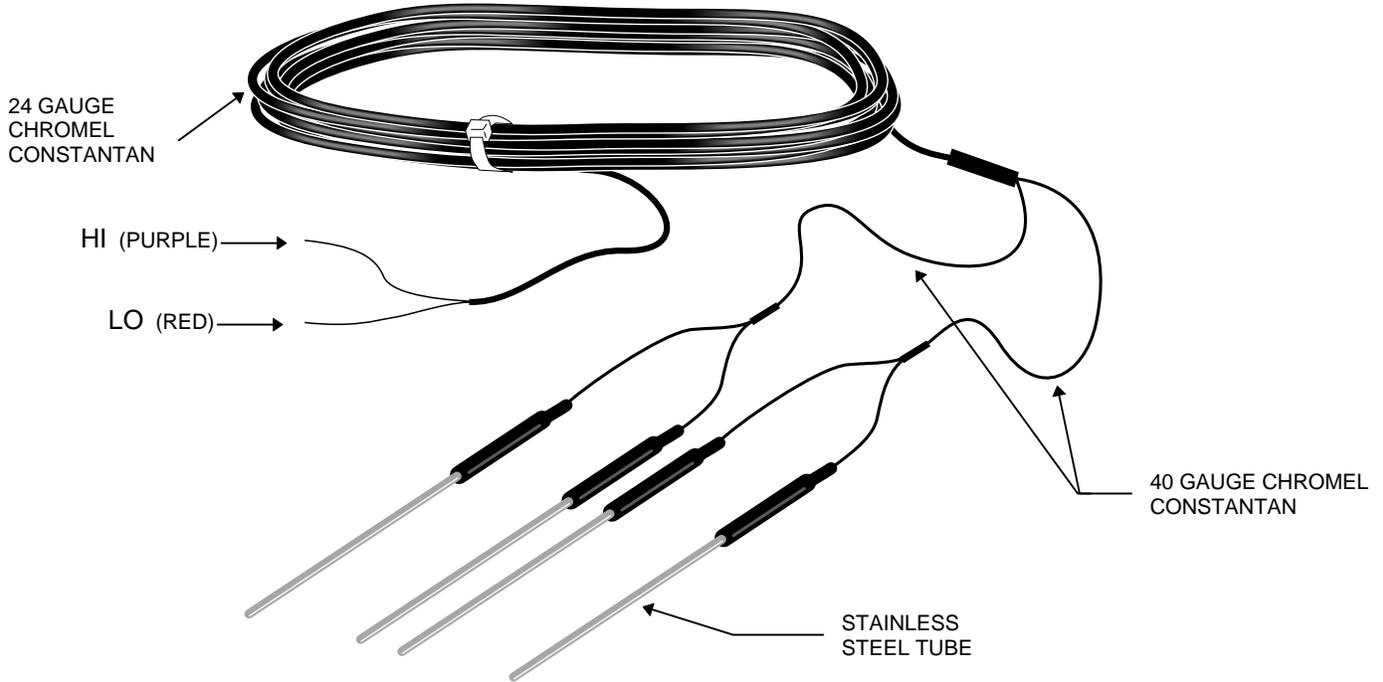
FIGURE 2.2-2. TCAV Spatial Averaging Thermocouple Probe

2.3 WIRING

Table 2.3-1 lists the connections to the CR23X for the standard Bowen ratio sensors measured by the example program. Because the air temperature measurements are so critical, the air temperature thermocouples are connected to differential channel 4 (the channel that is closest to the reference temperature thermistor). The input terminal strip cover for the CR23X must be installed once all connections have been made and verified (Section 13.4 of CR23X manual).

TABLE 2.3-1. CR23X/Sensor Connections for Example Program

CHANNEL	SENSOR	COLOR
1H	Q7.1	RED
1L	Q7.1	BLACK
⏚	SHIELD	CLEAR
2H	HYGROMETER PRT	GREEN
2L	HYGROMETER PRT	WHITE
⏚	HYGROMETER PRT	BLACK
3H	TCAV	PURPLE
3L	TCAV	RED
⏚	TCAV	CLEAR
4H	UPPER 0.003 TC - CHROMEL	PURPLE
4L	LOWER 0.003 TC - CHROMEL	PURPLE
⏚	UPPER/LOWER TCs - CONSTANTAN	RED/RED
	TC SHIELD	CLEAR/CLEAR
5H	HFT#1	BLACK
5L	HFT#2	WHITE/WHITE
⏚	HFT#1 AND HFT#2	CLEAR/CLEAR

6H	WIND SENTRY	RED
6L	CS615	GREEN
⏚	WIND SENTRY	WHITE/CLEAR
	CS615	BLACK/CLEAR
EX1	HYGROMETER EXCITATION	RED
EX2	WIND SENTRY	BLACK
GND	HYGROMETER	CLEAR
C1	PULSE FOR LOWER AIR INTAKE	GREEN
C2	PULSE FOR UPPER AIR INTAKE	WHITE
C3	PULSE TO **TURN ON POWER TO MIRROR AND PUMP (FLAG 6)**	BLACK
C4	PULSE TO **TURN OFF POWER TO MIRROR AND PUMP (FLAG 7)**	RED
C7	CS615 (TURN UNIT ON)	ORANGE
G	GROUND WIRE	CLEAR
PULSE		
1	WIND SENTRY	BLACK
⏚	WIND SENTRY	WHITE/CLEAR
2	CS615	GREEN
⏚	CS615	BLACK/CLEAR
+12 V	CS615	RED
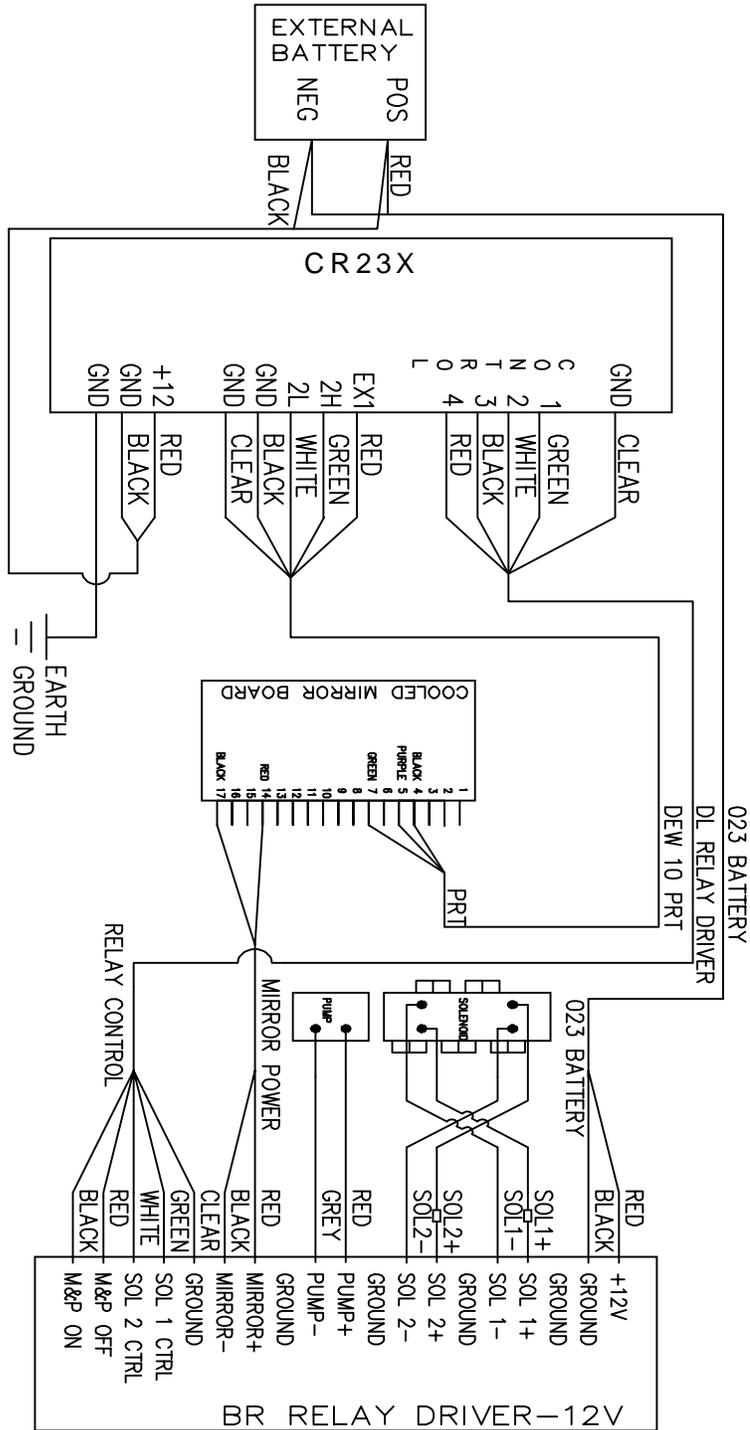
**FIGURE 2.3. A Block Diagram for the Connections between
the Datalogger, the BR Relay Driver and Components, and the External Battery.**

2.4 BATTERY CONNECTIONS

Two terminal strip adapters for the battery posts (P/N 4386) are provided with the 023A (Figure 2.4-1). These terminal strips will mount to the wing nut battery posts on most deep cycle lead acid batteries.
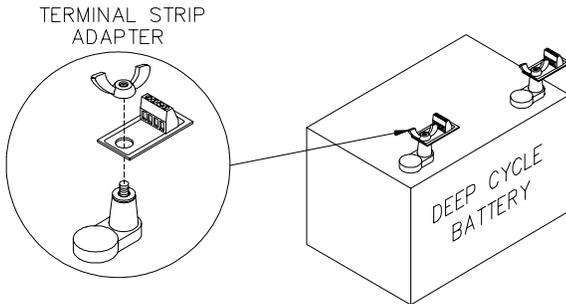
FIGURE 2.4-1. Terminal Strip Adapters for Connections to Battery

The MSX20R solar panel, BR relay driver, and CR23X each have a separate power cable. Once the system is installed, these power cables are then connected to the external battery (red to positive, black to negative). The CR23X power cable is shipped in the 023A enclosure and must be connected to the +12 V (red from power cable) and ground (black from power cable) terminals on the CR23X wiring panel.

2.5 SYSTEM STARTUP

To bring the Bowen ratio system on-line, turn on the datalogger, set the datalogger time, download the program, and set flag 6 high to activate the hygrometer and pump.

2.6 ROUTINE MAINTENANCE

Change air intake filters	1-2 weeks
Clean mirror and adjust bias	1-2 weeks
Clean thermocouples	as needed
Clean Radiometer domes	as needed

Filters are Teflon, 25 mm diameter with a 1 µm pore size, i.e., Nuclepore 130610 or Gelman 66154

To write an array to Final Storage, while replacing filters and cleaning thermocouples, set flag 4 high. Set flag 4 low when maintenance is complete. The time that the site maintenance

bean and ended will be written into Final Storage.

Before removing the filters, turn the pump/mirror off by setting flag 7 high. Install the clean filters with the glossy, textured side down. Be sure to remove any protective paper from the filter. Remove all debris from the fine wire thermocouples. A camel-hair brush and tweezers can be used to clean the thermocouples. To turn the hygrometer and pump on, set flag 6 high.

The thermocouples can also be dipped in a mild acid to dissolve spider webs. For example, muratic acid (hydrochloric acid) is available in most hardware stores. Rinse the thermocouples thoroughly with distilled water after dipping.

2.7 CLEANING THE DEW 10

Mirror cleaning and optical bias adjustment are important periodic maintenance functions. Adjustment of the optical bias determines the thickness of the dew layer on which the system reaches its control point. Proper adjustment of the bias is essential. The DEW 10 will not control on an excessively thick dew layer, whereas controlling on a thin layer requires more frequent mirror cleaning.

> **CAUTION:** Gently spin the cotton swab to clean the mirror. Use a dabbing motion to dry the mirror. Using excessive force to clean the mirror will scratch it.

1. Write time that site maintenance began by setting flag 4 high.

2. Shut off the thermoelectric cooler by sliding switch S1 toward the nearest end of the card, out of the operate position (OP) and into the balance position (BAL).

3. Remove the DEW 10 connector from the circuit board (Figure 2.7-1). Pull firmly on the DEW 10 until it slides out of the mirror block.

4. Locate the mirror, it is circular in shape and only the edge can be seen when looking straight into the mirror cavity. The mirror is mounted on a 45° angle within the mirror cavity.

Gently clean the mirror with a cotton swab and the blue cleaning solution. Remove any excess cleaning fluid by gently dabbing with a clean dry swab.

Wait at least 2 minutes before continuing to the next step. This will allow sufficient evaporation of the moisture from the mirror.

5. Place the DEW 10 back into the chilled mirror block and reconnect it to the circuit board.

To aid in reinserting the DEW 10 into the mirror block, twist the DEW 10 1/8 of a turn while firmly pushing it into the mirror block. Be sure the mirror cavity is parallel to the flow through the mirror block, i.e., vertical.

6. Use a small screwdriver to turn the potentiometer, R34, located on the top edge of the circuit board (Figure 2.6-1).

If the LED is on, turn the screw counter clockwise until the red LED turns off.

If the LED is not already on, turn the potentiometer clockwise until it turns on and then counter clockwise until it goes off.

Now, slowly turn the potentiometer clockwise until the LED comes on again.

7. Return the switch to its normal operating position. The LED will turn off several seconds after the switch is moved to the normal operating position.

8. Set flag 4 low to write the time that site maintenance ended.

Cleaning the mirror with a cotton swab does not result in a surface condition like the one reached after evaporation of a dew layer. Therefore, a more appropriate bias adjustment is reached with a mirror surface on which a dew layer has been formed and then evaporated.

By adding two steps to the above procedure, a more appropriate bias adjustment can be made and the period between required mirror cleaning can be further extended. These additional steps are:

9. Allow the system to run under normal operation for 8 to 24 hours, after completing steps 1 through 8.

10. Now repeat step 1, 2, and 6 through 8.
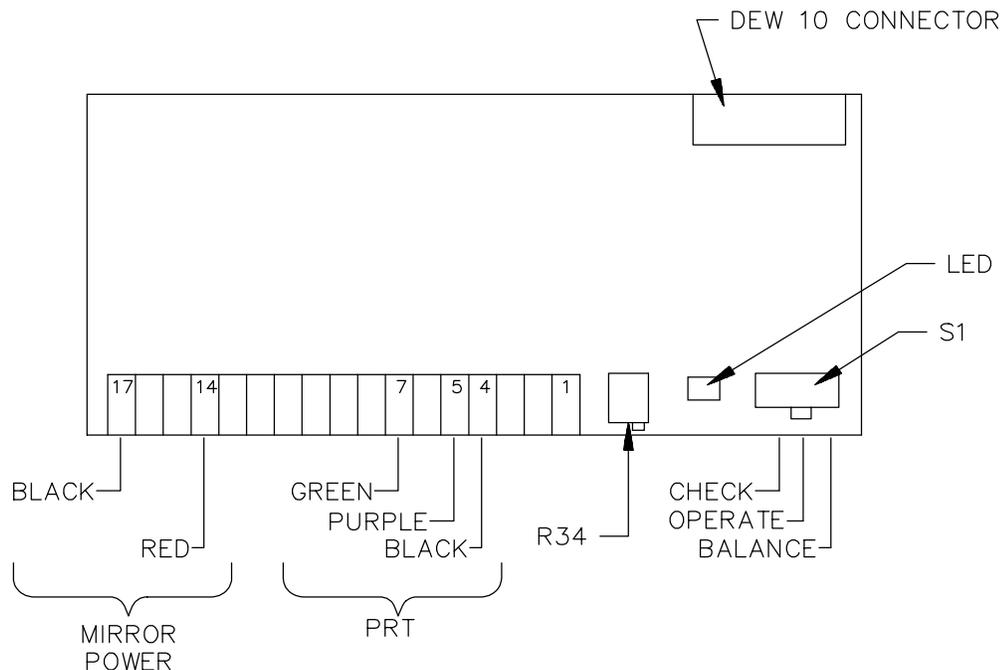
FIGURE 2.7-1. DEW 10 Circuit Board

SECTION 3. SAMPLE CR23X PROGRAM

The example program is available on the Campbell Scientific FTP site, ftp://ftp.campbellsci.com/pub/ outgoing/files/br_023a.exe. The example program measures the standard Bowen ratio inputs: vapor pressure and air temperature gradients, net radiation, and soil heat flux (flux at 8 cm and change in temperature of the soil layer above). If additional measurements are to be made or if a different installation is to be used, the program will have to be altered. Note that even if this exact installation is used, the correct calibration (multiplier and offset) must be entered for the net radiometer and soil heat flux plates.

Table 3-1 is a flow chart of the example program and Table 3-2 lists the output generated by the program.

*Power to the pump and cooled mirror is switched on and off by the datalogger. This can be under manual control by setting a flag in the *6 Mode **(flag 6 to turn on, flag 7 to turn off)**, or automatically by the program if the battery voltage drops below 11.5 volts (subroutine 2).*

TABLE 3-1. Sample CR23X Bowen Ratio Program Flow Chart

Table 1
1 Second Execution Interval
Measure Panel Temperature Measure Lower Thermocouple (Single Ended) Measure Upper Thermocouple (Differential) Measure RTD on Cooled Mirror Subtract Upper TC Temp. from the Lower TC Temp. Calculate RTD R/Ro Calculate RTD Temperature Calculate Vapor Pressure

Flag 5 Set?	
Yes	No

20 Minute Interval ?	
Yes	No

Set Flag 0 (Output)	

Flag 4 Set ?	
Yes	No

Set Flag 0 (Output) Set Flag 5	

[process] Day, Hour:Minute (smpl) Panel Temperature (smpl) Lower Temperature (avg) Temperature Gradient (avg)

Flag 2 Set ?	
Yes	No

Set Flag 9 (Disable Intermediate Processing)	

Flag 1 Set ?	
Yes	No

Set Flag 9 (Disable Intermediate Processing)	

[process] Upper Dew Point (avg) Upper Vapor Pressure (avg) Reset Flag 9

Flag 2 Reset ?	
Yes	No

Set Flag 9 (Disable Intermediate Processing)	

Flag 1 Set ?	
Yes	No

Set Flag 9 (Disable Intermediate Processing)	

[process] Lower Dew Point (avg) Lower Vapor Pressure (avg)

Table 2		
10 Second Excitation Interval		
40 Second Interval ?		
Yes		No
Reset Flag 1		
Flag 5 Set ?		
Yes		No
Flag 4 Reset ?		
Yes	No	
Call Subroutine 1		
2 Minute Interval ?		
Yes		No
Set Flag 1		
4 Minute Interval ?		
Yes	No	
Set Port 2 High Set Flag 2	Set Port 1 High Reset Flag 2	
Delay 0.01 Seconds Set Port 1 Low Set Port 2 Low		
Measure Battery Voltage Measure Net Radiation		
Net Radiation Positive ?		
Yes		No
Call Subroutine 3 (wind speed correction on positive radiation)		Call Subroutine 4 (wind speed correction on negative radiation)
Measure 2 Soil Heat Flux Plates Measure Soil Temperature (Layer Average) Scale Heat Flux Measurements Wind Speed Wind Direction		
Ten Minutes Into Interval ?		
Yes		No
Measure CS615		
Last 10 Minutes of a 20 Minute Interval ?		
Yes		No
Compute Average Soil Temperature		
20 Minute Interval ?		
Yes		No
Calculate 10 Minute Soil Temp. (avg) Calculate Change from Previous Soil Temp. [output process] Day, Hour:Minute Net Radiation (avg) 2 Soil Heat Flux Plates (avg) Soil Temp. 10 min. avg. (smpl) Change in Soil Temp. (smpl) CS615 mSec Soil Water Content Soil Water Content Corrected for Temp. Battery (avg)		
Call Subroutine 2 (battery check)		

Subroutine 1
Output the time processing is re-enabled
Reset Flag 5 (Re-enable Output)
[output process]
Day, Hour:Minute

Subroutine 2
Turn the cooled mirror and pump on/off in response to a user flag or battery voltage

Flag 6 Set ?	
Yes	No
Set Port 3 High (Turn on Pump and Mirror)	

Reset Flag 6

Flag 7 Set ?	
Yes	No
Set Port 4 High (Turn off Pump and Mirror)	

Reset Flag 7

Battery Volts < 11.5 ?	
Yes	No

Flag 3 Reset ?		Flag 3 Reset ?	
Yes	No	Yes	No
			Battery Voltage ≥ 12
			Yes / No
Set Port 4 High		Set Port 3 High	
Delay 0.01 Seconds		Delay 0.01 Seconds	
Set Port 4 Low		Set Port 3 Low	
Set Flag 3		Reset Flag 3	
[output process]		[output process]	
Day, Hour:Minute		Day, Hour:Minute	
Battery Voltage (smpl)		Battery Voltage (smpl)	

Subroutine 3
Positive net radiation
Apply positive wind speed correction to positive Net Radiation

Subroutine 4
Negative net radiation
Apply negative wind speed correction to negative Net Radiation

TABLE 3-2. Output From Example Bowen Ratio Program

01: 110 20 minute Bowen ratio data
02: Day
03: hhmm
04: Avg Reference Temperature
05: Avg T low
06: Avg dT
07: Avg DP low
08: Avg VP low
09: Avg DP high
10: Avg VP high

01: 237 20 minute Bowen ratio data
02: Day
03: hhmm
04: Avg RN
05: Avg soil heat flux #1
06: Avg soil heat flux #2
07: Avg soil temp (Last 10 min)
08: Change from previous soil temp
09: Avg wind speed
10: Avg wind direction
11: Standard deviation of wind direction
12: CS615 period
13: Volumetric soil water content
14: Volumeric soil water content corrected for temperature
15: Avg battery voltage

01: 302 Beginning of site maintenance
02: Day
03: hhmm

01: 303 End of site maintenance
02: Day
03: hhmm

01: 317 Pump and cooled mirror shut off due to low battery
02: Day
03: hhmm
04: Batt volts

01: 328 Pump and cooled mirror turned on, batt recharged
02: Day
03: hhmm
04: Batt volts

SECTION 4. CALCULATING FLUXES USING SPLIT

SPLIT (PC208W software) can be used to calculate the fluxes from the Bowen ratio measurements. This section describes these calculations on the data output from the example datalogger program. It requires two passes with SPLIT to compute the fluxes. The first pass operates on the raw data files generated by the datalogger. The definitions of points in this data is given in Table 3-2 which is the Output from the sample program. The output file from this first pass (RAWBOW.PRN) is defined in the parameter file RAWBOW.PAR. The fluxes are then calculated by SPLIT with the parameter file CALCBOW.PAR.

The example SPLIT parameter files: SERVICE.PAR, SHUTDOWN.PAR, RAWBOW.PAR, and CALCBOW.PAR are on the Campbell Scientific, Inc. FTP site, ftp://ftp.campbellsci.com/pub/outgoing/files/ br_023a.exe.

4.1 DATA HANDLING

Before calculating the surface fluxes, first Quality Control the raw data. Use the SPLIT parameter files SERVICE.PAR and SHUTDOWN.PAR to determine when the station was down for service or when it shut itself down because of low battery voltage.

Next, combine the air temperature and vapor pressure gradients with net radiation, soil heat flux, soil temperature, wind speed, and wind direction, using the SPLIT parameter file RAWBOW.PAR.

This parameter file assumes that the data files from the datalogger were saved on disk under the name BOWEN.DAT. It creates a file with the raw data necessary to calculate fluxes RAWBOW.PRN.

Plot the data in RAWBOW.PRN, check the temperature and vapor pressure gradient, soil heat flux and temperature, and net radiation for anomalous readings. Check the wind speed and direction data to determine if the fetch conditions are adequate.

4.2 CALCULATING FLUXES

Once the necessary data is in one file the fluxes can be calculated. The constants and parameters necessary for calculating the fluxes are listed in Table 4.2-1.

Most of the calculations in CALCBOW.PAR are explained in the overview in Section 1. The method used to calculate the heat storage term and hence soil heat flux at the surface is explained below.

The soil heat flux at the surface is calculated by adding the measured flux at a fixed depth, d, to the energy stored in the layer above the heat flux plates. The specific heat of the soil and the change in soil temperature, ΔT_s, over the output interval, t, are required to calculate the stored energy.

The heat capacity of the soil is calculated by adding the specific heat of the dry soil to that of the soil water. The values used for specific heat of dry soil and water are on a mass basis. The heat capacity of the moist is given by:

$$C_s = \rho_b\left(C_d + \theta_m C_w\right) = \rho_b C_d + \theta_v \rho_w C_w \qquad (9)$$

$$\theta_m = \frac{\rho_w}{\rho_b}\theta_v \qquad (10)$$

where C_S is the heat capacity of moist soil, ρ_b is bulk density, ρ_w is the density of water, C_d is the heat capacity of a dry mineral soil, θ_m is soil water content on a mass basis, θ_v is soil water content on a volume basis, and C_w is the heat capacity of water.

This calculation requires site specific inputs for bulk density, mass basis soil water content or volume basis soil water content, and the specific heat of the dry soil. Bulk density and mass basis soil water content can be found by sampling (Klute, 1986). The volumetric soil water content is measured by the CS615 soil water content reflectometer. The value used for the heat capacity of dry soil in the example SPLIT parameter file is a reasonable value for most mineral soils (Hanks and Ashcroft, 1980).

The storage term is then given by Eq. (3).

$$S = \frac{\Delta T_s\, C_s\, d}{t} \qquad (11)$$

SECTION 4. CALCULATING FLUXES USING SPLIT

Atmospheric pressure is a site-specific input. Pressure can be measured at the site or obtained from a local meteorological station. An estimate of pressure can be calculated for the site using a standard atmosphere with the following equation:

$$P = 101.325 \left[1 - \frac{E}{44307.69231} \right]^{5.25328} \qquad (12)$$

where P is in kPa and the elevation, E, is in meters (Wallace and Hobbs, 1977).

TABLE 4.2-1. Input Values for Flux Calculations

VARIB.	VALUE	UNITS	DESCRIPTION
CP	1.01	kJ/(kg K)	Specific heat of air
CW	4190.0	J/(kg K)	Specific heat of water
CS*	840.0	J/(kg K)	Specific heat of dry soil **(estimate)**
EW**	2450.0	kJ/kg	Latent heat of vaporization at 20°C
P*	87.18	kPa	Atmospheric pressure, measure or calculate for elevation
T**	1200	s	Output interval
D**	0.08	m	Depth to flux plates
BD*	1200	kg/m³	Soil bulk density, **must be measured for site**
W		vol-H_2O/bulk vol-soil	Soil water content, volume basis, measured by the CS615
F		W/m²	Soil heat flux measured at 8 cm.
S		W/m²	Heat stored, calculated from soil heat capacity and measured change in temperature.
G		W/m²	Soil heat flux at surface (F+S)
RN		W/m²	Net radiation, measured
BR		—	Bowen ratio
LE		W/m²	Latent heat flux
H		W/m²	Sensible heat Flux
	0.622		Molecular weight of water/molecular weight of air.

* These values are for a particular site. Correct values must be entered for the site under study.

** These values may need to change if the program or installation is changed.

APPENDIX A. REFERENCES

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APPENDIX B. 023 BOWEN RATIO (PRE JULY 1993)

WATER VAPOR MEASUREMENT
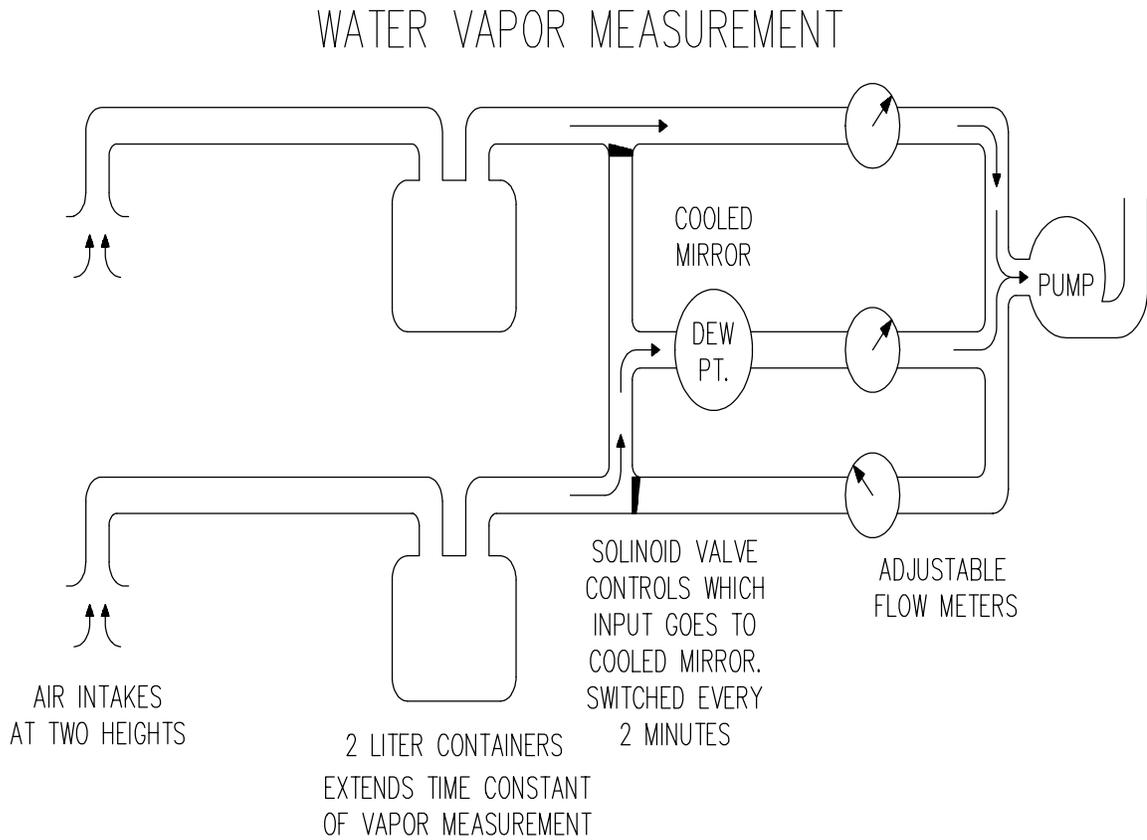
FIGURE B-1. 023 Bowen ratio Vapor Measurement System with Three Flowmeters.