App. Note Code: 4-D

APPLICATION NOTE

On-Line Estimation of Grass Reference Evapotranspiration with the Campbell Scientific Automated Weather Station

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With increasing pressure on water supplies and concerns over the groundwater contamination which results from overirrigation, it is becoming increasingly important to know how much water crops need. This information is most useful if it is supplied in real-time as the water loss occurs. Fortunately, modern dataloggers and sensors are capable of making the measurements and computations necessary to provide this information. This application note describes the computations necessary for estimating grass reference evapotranspiration (ET_o). The reference crop is defined as a short grass crop that is not short of water.

A number of methods have been used to estimate grass reference evapotranspiration. Many are reviewed and evaluated by Jensen et al. (1990). The most successful are combination methods that use measurements of absorbed radiant energy, wind, and atmospheric vapor deficit. A number of studies have shown that the Penman-Monteith form of the combination equation consistently outperforms the others. This equation includes more of the factors that influence crop water loss than the other equations, and is therefore expected to provide better estimates. It has not been used in the past in operational applications because of its additional computational complexity and the need to define standard values for the reference crop. Past grass reference ET_o computations have usually been made using daily, rather than hourly data. More empirical equations, which were derived using daily average data, might be expected to work better under these conditions. However, with the capabilities of microprocessor-based dataloggers to do on-line computations, many limitations have been removed, and the more physically sound Penman-Monteith equation has become feasible for operational applications.

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The Penman-Monteith Equation

The Penman-Monteith (PM) equation can be written as:

$$ET_o = \frac{\Delta(R_n - G)}{\lambda(\Delta+\gamma^*)} + \frac{\gamma^* M_w (e_a - e_d)}{R\Theta r_v (\Delta+\gamma^*)} \quad (1)$$

ET_o	Potential evaporation (kg m^{-2} s^{-1} or mm s^{-1})
R_n	Net radiation (kW m^{-2})
G	Soil heat flux density (kW m^{-2})
M_w	Molecular mass of water (0.018 Kg mol^{-1})
R	Gas constant (8.31 X 10^{-3} kJ mol^{-1} K^{-1})
Θ	Kelvin temperature (293 K)
e_a-e_d	Vapor pressure deficit of the air (kPa)
λ	Latent heat of vaporization of water (2450 kJ kg^{-1})
r_v	Canopy plus boundary layer resistance for vapor (s m^{-1})
Δ	Slope of the saturation vapor pressure function (Pa °C^{-1})
γ^*	Apparent psychrometer constant (Pa °C^{-1})

Details on the derivation of this equation can be found in Monteith and Unsworth (1990) and Campbell (1977). The Automated Weather Station measures air temperature, relative humidity, incident solar radiation, and wind speed. A number of conversions and assumptions is needed to convert these measurements to the parameters for the PM equation. We will generally follow the recommendations suggested by Smith (1991), since these have been recommended as standards for use throughout the world by the Food and Agriculture Organization of the United Nations.

The net radiation is the sum of the net solar radiation and the net long-wave radiation. This is approximated as:

$$R_n = a_s S_t + L_{ni} \quad (2)$$

Where a_s is the absorptivity of the crop for solar radiation, S_t is the incident solar radiation measured by the datalogger, and L_{ni} is the atmospheric radiant emittance minus the crop emittance at air temperature. Monteith and Unsworth (1990) show that, under clear skies, L_{ni} is closely approximated by:

$$L_{nic} = 0.0003\ T_a - 0.107\ (\text{kW m}^{-2}) \quad (3)$$

where T_a is the air temperature in degrees Celsius (°C). Under cloudy skies, L_{ni} increases and approaches zero. We estimate cloudiness from the ratio of measured to potential solar irradiance during daylight hours: S_t/S_o. A cloudiness function is then computed as:

$$f(S_t/S_o) = 1 - 1/[1+0.034 \exp(7.9\, S_t/S_o)] \tag{4}$$

The net isothermal long-wave for cloudy skies can then be calculated by multiplying the value obtained from the cloudy function with the approximation of the long-wave radiation for clear skies:

$$L_{ni} = f(S_t/S_o)\, L_{nic} \tag{5}$$

Equation 4 requires the computation of S_o, the potential solar radiation on a horizontal surface outside the earth's atmosphere. This is calculated from:

$$S_o = 1.36 \sin\phi \tag{6}$$

where 1.36 kW m^{-2} is the solar constant, and ϕ is the elevation angle of the sun. Sin ϕ is computed from:

$$\sin\phi = \sin d \sin l + \cos d \cos l \cos[15(t-t_o)] \tag{7}$$

where d is the solar declination angle, l is the latitude of the site, t is clock time, and t_o is the time of solar noon. The declination angle is often evaluated using several terms of a Fourier series, but, since Campbell Scientific dataloggers are particularly adept at evaluating polynomials, we chose to approximate sin d using the following polynomial:

$$\sin d = -0.37726-0.10564j+1.2458j^2-0.75478j^3+0.13627j^4-0.00572j^5 \tag{8}$$

where j is (day of the year)/100. The cosine is computed from the trigonometric identity:

$$\cos d = (1 - \sin^2 d)^{1/2} \tag{9}$$

For running the PM algorithm, we assume the user always sets the clock to standard time (not daylight savings time). The time, t, needed for Eq. 7 is therefore just the datalogger clock time less half the time increment from the last ET_o computation. The time of solar noon is given by:

$$t_o = 12.5 - L_c - t_e(hr) \tag{10}$$

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where L_c is a longitude correction and t_e is the "Equation of Time." The longitude correction is a user-supplied parameter. It is calculated by determining the difference between the longitude of the site and the longitude of the standard meridian. Standard meridians are at 0°, 15°, 30°..345°. Generally time zones run approximately ±7.5° on either side of a standard meridian, but this varies depending on political boundaries (see Figure 1). The user should check an atlas to get both the longitude and the standard meridian for the site (as well as the latitude, which is also needed for Eq. 7). The longitude correction is computed from:

$$L_c = (L_s - L)/15. \tag{11}$$

If the longitude of the site were L=117°, and the longitude of the standard meridian were L_s=120°, L_c would be (120-117)/15 = 0.2 hr. If the longitude of the site were 123°, L_c would be -0.2 hr.

The Equation of Time is an additional correction to the time of solar noon that depends on day of the year. Again, we used a polynomial for the computation. Two equations were used, one for the first half of the year, the other for the second half. For the first half (day of year ≤180),

$$t_e = -0.04056-0.74503j+0.08823j^2+2.0516j^3-1.8111j^4+0.42832j^5, \tag{12}$$

where j=(day of the year)/100. For day of the year>180,

$$t_e = -0.05039-0.33954j+0.04084j^2+1.8928j^3-1.7619j^4+0.4224j^5, \tag{13}$$

where j=(day of the year-180)/100.

Latitude must also be taken into account. For latitudes above the equator, the value used will be positive. Below the equator, the value for latitude will be negative.

Evapotranspiration occurs mainly during daytime hours when net radiation is positive. When R_n is positive, the soil heat flux density can be reliably estimated as a fraction of R_n. For complete canopy cover (the condition specified for reference ET_o), we can use:

$$G = 0.1\ R_n \tag{14}$$

When S_t = 0 (night), we can use G = 0.5 R_n or G = 0.5 L_{ni}.

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The variable, Δ, is the slope of the saturation vapor pressure function, and depends only on air temperature. We use a polynomial to evaluate Δ:

$$\Delta = 45.3 + 2.97\ T + 0.0549\ T^2 + 0.00223\ T^3 \quad (\mathrm{Pa}\ ^\circ\mathrm{C}^{-1}) \qquad (15)$$

for the temperature range of -5° to 45°C.

The apparent psychrometer constant, γ^*, is calculated from:

$$\gamma^* = \gamma\ r_v/r_a \qquad (16)$$

where γ is the thermodynamic psychrometer constant, r_v is the combined canopy and aerodynamic resistance to water vapor, and r_a is the convective resistance for heat transfer. The vapor resistance is computed from $r_v = r_a + r_c$ where r_c is the canopy resistance. Smith (1991) gives, as standard for a reference crop, r_c = 70 s m^{-1}. At night, the stomatal resistance increases so the value of 700 s m^{-1} is assigned to r_c when solar power drops below 10 W m^{-2}. He also gives the relationship, $r_a = 209/u_2$, where u_2 is the wind speed measured at a height of 2 m above the ground. For wind measured at 3 m height (u_3), the relationship is $r_a = 240/u_3$. These values are a simple reduction of the equation:

$$r_a = \ln\left[\frac{z_u - d}{z_{om}}\right]\ln\left[\frac{z_t - d}{z_{oh}}\right]/k^2 u_{zu} \qquad (17)$$

where k = 0.41, z_u is the height of the anemometer above the soil surface and z_t is the height of the hygrometer (temperature and RH) above the soil surface. If d is 0.67 H and z_{om} is 0.12 H for clipped grass with $z_{oh} = 0.1\ z_{om}$ (Allen et al., 1989 and ASCE 70), then, for 0.12 m grass, $r_a = 209/u_2$ for a 2 m anemometer, RH and temperature height and $r_a = 240/u_3$ for a 3 m anemometer, RH, and temperature height.

The thermodynamic psychrometer constant has a weak temperature dependence, which we ignore, and a pressure dependence, which we account for. At sea level and 20°C, γ = 67.3 Pa. The value decreases in direct proportion to atmospheric pressure, so we multiplied this value by the ratio of atmospheric pressure to sea level pressure, which we calculated from the altitude of the site:

$$P/P_o = \exp(-A/8500) \quad \text{or} \quad P/P_o = \exp(-B/27889) \qquad (18)$$

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where A is the altitude in meters or B is the altitude in feet. Altitude is another value that the user must supply.

The Kelvin temperature in the denominator of Eq. 1 was set at 293 K, so that the combination, $M_w/R\Theta$, could be pre-computed and entered as a constant in the program. While this has a small temperature dependence, it is certainly negligible compared to the other uncertainties in Eq. 1.

Vapor pressures in Eq. 1 are computed from the air temperature and relative humidity measurements. The saturation vapor pressure at air temperature, e_a, is obtained from the datalogger saturation vapor pressure function, with air temperature as the argument. The saturation vapor pressure at dew point temperature, e_d, (or air vapor pressure) is obtained from $e_d = h_r e_a$, where h_r is the relative humidity (as a fraction, not a percent).

Implementing the Penman Monteith Calculation in the CR10X

The attached program example implements the PM calculation in our CR10X. There are a number of comments which show how the equations are implemented. The calculations are done in subroutine 1. The user-supplied information is shown in steps 2, 3, and 4 of Table 3. The wind speed factor is set for a height of 3 m. If the anemometer is at a different height, this value should be changed in step 67 of Table 3.

Weather variables are sampled every 10 s; hourly values for grass reference crop ET_o (E_p) are computed from the sampled data hourly. The hourly values are stored in final memory and also summed to give a daily value. The time of day for output is set in steps 56, 62, and 70 in Table 1, so the daily sums are from the time set on one day to that same time on the next. Normally this would be set at midnight (1440), but an irrigation manager might want an earlier readout time so that night time irrigation could be planned at the end of each day.

Users of this program should be aware of its limitations. We feel that it represents the best available method for computing grass reference crop evapotranspiration. However, crops differ in their water requirements. The ET of a crop depends on several factors in addition to ET_o, including stage of development, crop height, ground cover, etc. Engineers account for these factors by using a crop coefficient to multiply ET_o. For a complete cover of short grass, the crop coefficient is 1. Contact Campbell Scientific Environmental Application Engineering Department for a list of crop coefficients and a discussion of their use.

Another important consideration is the quality of the input data. No matter how good the algorithm, if the measurements are faulty, the predictions will be useless. The user needs to make sure that the latitude, longitude correction, and altitude supplied to the program are correct, and that the datalogger clock is set to correct standard time. If these values are wrong, the estimates of the long-wave radiation will be wrong. It is also important to use a regular schedule of maintenance and recalibration assuring the sensors operate correctly. For example, if the wind speed sensor were to malfunction and give a wind speed reading of zero, γ^* would become infinite, and the algorithm would predict zero ET_o, regardless of the actual ET_o. As the algorithms become more sophisticated and accurate, the need for accurate environmental data increases. Calibration on anemometers, pyranometers, and humidity sensors should be checked at least annually against standards.

References

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Monteith, J. L. and M. H. Unsworth. 1990. Principles of Environmental Physics, 2nd Ed., Edward Arnold, London. 289 p.

Smith, M. 1991. Report on the expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements. Food and Agriculture Organization of the United Nations, Rome, Italy.

Allen, R. G., M. E. Jensen, J. L. Wright, and R. D. Burman. 1989. Operational estimates of reference evapotranspiration. Agron. J. 81(4):650-662.

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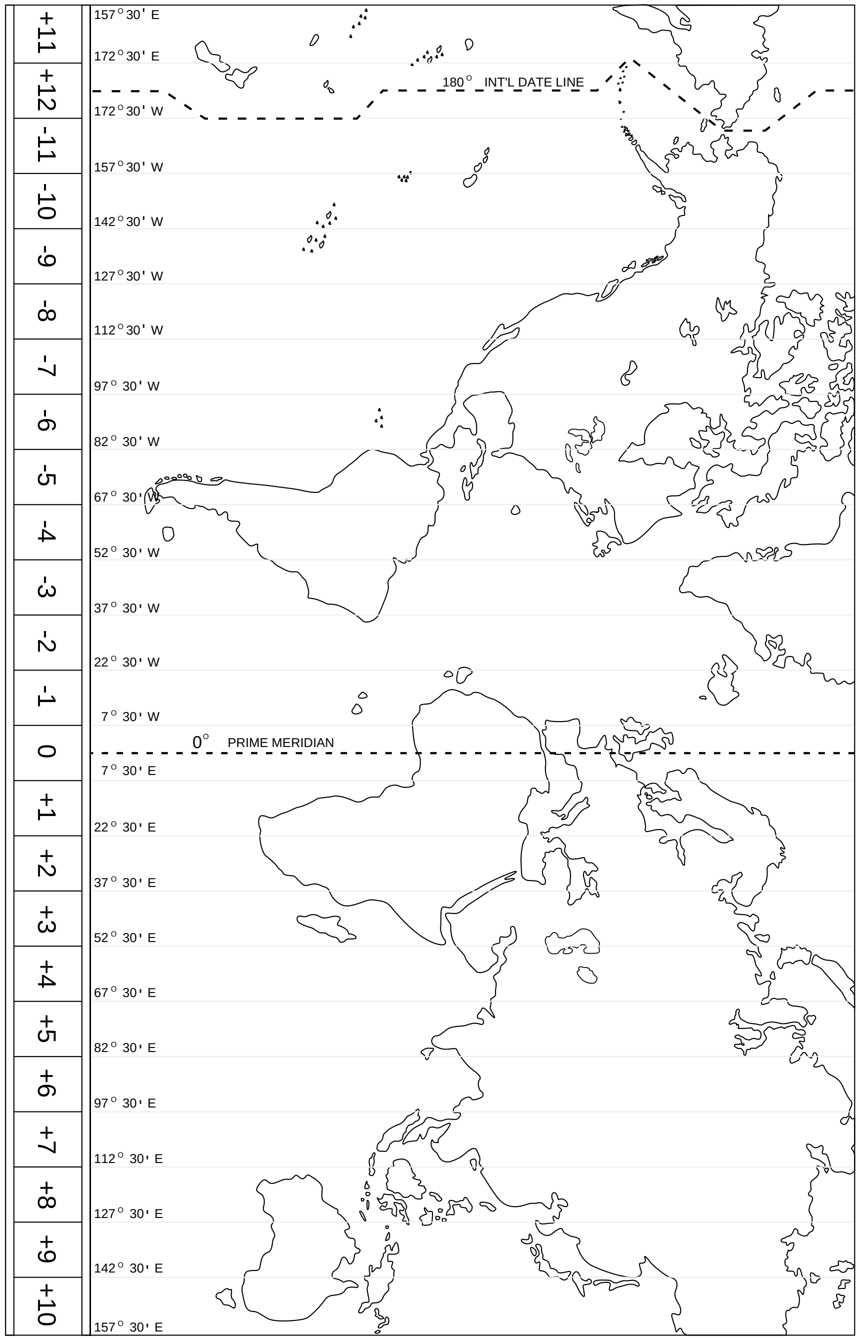

FIGURE 1. Time Zones

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```
;{CR10X}
;
;Program: MetData 1 weather station program that calculates
;hourly Penman-Monteith Potential Evapotranspiration (ETo).
;
;Date: 15.June.1998
;
;*B CR10X STATUS/ON-BOARD FIRMWARE WITH PRO-
GRAM LOADED
;-----------------------------------------------------
;01: 18927
;02: 26114
;03: 0256
;04: 00
;05: 00
;06: 1.0000
;07: 0007
;08: 3.152.0
;09: 00
;10: 00
;11: 0.0000
;
;INPUT CHANNEL USAGE
;--------------------------------
;S.E. CHANNEL 1 - Relative Humidity (HMP45C)
;S.E. CHANNEL 2 - Air Temperature (HMP45C)
;S.E. CHANNEL 3 - Wind Direction (034A)
;DIFF CHANNEL 3 - Pyranometer (LI200X)
;S.E. CHANNEL 10 - Enclosure Relative Humidity
;
;EXCITATION CHANNEL USAGE
;-------------------------------
;E2 - Wind Direction (034A)
;
;PULSE CHANNEL USAGE
;-------------------------------
;P1 - Wind Speed (034A)
;P2 - Tipping Rain Bucket (TE525)
;
;CONTROL PORT USAGE
;-------------------------------
;C1 - Relative Humidity and Air Temperature (HMP45C)
;
;FINAL STORAGE DATA ARRAY DEFINITIONS
;========================================
```


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```
;HOURLY DATA
;----------------------------------------
;1  Array ID - 129
;2  Year
;3  Julian Day
;4  Hour,Minute (HHMM; Midnight = 2400 hours)
;5  Average Air Temp - °C
;6  Sample Relative Humidity - %RH
;7  Average Vapor Pressure - KPa
;8  Average Solar Flux Density - KW/m²
;9  Hourly ETo Total - inch/hour
;10 Average Wind Speed - miles/hour
;11 Average Vector Wind Direction - degrees
;12 Standard deviation of Wind Direction
;13 Total Precipitation - inches/hour
;
;DAILY DATA (@MIDNIGHT)
;---------------------------------------
;1  Array ID - 139
;2  Year
;3  Julian Day
;4  Hour,Minute (HHMM; Midnight = 2400 hours)
;5  Average Air Temp - °F
;6  Maximum Air Temp - °F
;7  Minimum Air Temp - °F
;8  Average Vapor Pressure - KPa
;9  Maximum Vapor Pressure - KPa
;10 Minimum Vapor Pressure - KPa
;11 Average Solar Flux Density - KW/m²
;12 Daily ETo Total - inches/day
;13 Maximum Wind Speed - miles/hour
;14 Average Wind Speed - miles/hour
;15 Total Precipitation - inches/day
;16 Maximum Battery Voltage - DC Volts
;17 Minimum Battery Voltage - DC Volts
;18 Maximum Datalogger Temp (CR10X) - °C
;19 Minimum Datalogger Temp (CR10X) - °C
;20 Maximum Enclosure Relative Humidity - %RH
;21 Minimum Enclosure Relative Humidity - %RH
;22 Program Signature
```

```
*Table 1 Program
  01:     10.0000   Execution Interval (seconds)

01:  Batt Voltage (P10)
  1:        1          Loc [ Batt_Volt ]

02:  Internal Temperature (P17)
  1:        2          Loc [ CR10Tmp_C ]

03:  Do (P86)
  1:       41          Set Port 1 High

04:  Excitation with Delay (P22)
  1:        1          Ex Channel
  2:        0          Delay W/Ex (units = 0.01 sec)
  3:       15          Delay After Ex (units = 0.01 sec)
  4:        0          mV Excitation

05:  Volt (SE) (P1)
  1:        1          Reps
  2:       25          2500 mV 60 Hz Rejection Range
  3:        2          SE Channel
  4:        3          Loc [ AirTemp_C ]
  5:         .1        Mult
  6:      -40          Offset

06:  Z=X*F (P37)
  1:        3          X Loc [ AirTemp_C ]
  2:        1.8        F
  3:        4          Z Loc [ AirTemp_F ]

07:  Z=X+F (P34)
  1:        4          X Loc [ AirTemp_F ]
  2:       32          F
  3:        4          Z Loc [ AirTemp_F ]

08:  Volt (SE) (P1)
  1:        1          Reps
  2:       25          2500 mV 60 Hz Rejection Range
  3:        1          SE Channel                       Record
  4:        5          Loc [ RH       ]                 humidity as a
  5:         .001      Mult                             fraction.
  6:        0          Offset
```

```
09:  Do (P86)
  1:      51        Set Port 1 Low

10:  If (X<=>F) (P89)
  1:       5        X Loc [ RH       ]
  2:       3        >=
  3:       1        F
  4:      30        Then Do

11:  If (X<=>F) (P89)
  1:       5        X Loc [ RH       ]
  2:       4        <
  3:       1.09     F
  4:      30        Then Do

12:  Z=F (P30)
  1:       1        F
  2:       0        Exponent of 10
  3:       5        Z Loc [ RH       ]

13:  End (P95)

14:  End (P95)

15:  Saturation Vapor Pressure (P56)
  1:       3        Temperature Loc [ AirTemp_C ]
  2:      35        Loc [ Sat_VP    ]

16:  Z=X*Y (P36)
  1:      35        X Loc [ Sat_VP    ]
  2:       5        Y Loc [ RH        ]
  3:      34        Z Loc [ VP_kPa    ]

17:  Z=X*F (P37)
  1:       5        X Loc [ RH       ]
  2:     100        F
  3:       5        Z Loc [ RH       ]

18:  Z=X-Y (P35)
  1:      35        X Loc [ Sat_VP    ]
  2:      34        Y Loc [ VP_kPa    ]
  3:      36        Z Loc [ VPD_kPa   ]
```

```
19:  Volt (Diff) (P2)
 1:        1          Reps
 2:       22          7.5 mV 60 Hz Rejection Range
 3:        3          DIFF Channel
 4:        6          Loc [ Slr_kWm2  ]
 5:         .2        Mult
 6:        0          Offset

20:  If (X<=>F) (P89)
 1:        6          X Loc [ Slr_kWm2  ]
 2:        4          <
 3:        0          F
 4:       30          Then Do

21:  Z=F (P30)
 1:        0          F
 2:        0          Exponent of 10
 3:        6          Z Loc [ Slr_kWm2  ]

22:  End (P95)

23:  Pulse (P3)
 1:        1          Reps
 2:        1          Pulse Channel 1
 3:       22          Switch Closure, Output Hz
 4:       41          Loc [ WS_ms     ]
 5:         .799      Mult
 6:         .2811     Offset

24:  Z=X*F (P37)
 1:       41          X Loc [ WS_ms     ]
 2:        2.237      F
 3:        7          Z Loc [ WS_mph    ]

25:  Excite-Delay (SE) (P4)
 1:        1          Reps
 2:        5          2500 mV Slow Range
 3:        3          SE Channel
 4:        2          Excite all reps w/Exchan 2
 5:        2          Delay (units 0.01 sec)
 6:     2500          mV Excitation
 7:        8          Loc [ Wind_Dir  ]
 8:        0.288      Mult
 9:        0          Offset
```

```
26:  If (X<=>F) (P89)
  1:        8          X Loc [ Wind_Dir  ]
  2:        3          >=
  3:      360          F
  4:       30          Then Do

27:  Z=X+F (P34)
  1:        8          X Loc [ Wind_Dir  ]
  2:     -360          F
  3:        8          Z Loc [ Wind_Dir  ]

28:  End (P95)

29:  Pulse (P3)
  1:        1          Reps
  2:        2          Pulse Channel 2
  3:        2          Switch Closure, All Counts
  4:        9          Loc [ Rain_inch ]
  5:         .01       Mult
  6:        0          Offset

30:  Volt (SE) (P1)
  1:        1          Reps
  2:       25          2500 mV 60 Hz Rejection Range
  3:       10          SE Channel
  4:       28          Loc [ Encl_RH   ]
  5:         .1        Mult
  6:        0          Offset

; Compute hourly averages of solar radition, air temperature,
; vapor pressure deficit, and wind speed to be used with the ETo
; algorithm.  Values go into input locations 37-40.

31:  If time is (P92)
  1:        0          Minutes (Seconds --) into a
  2:       60          Interval (same units as above)
  3:       10          Set Output Flag High (Flag 0)

32:  Set Active Storage Area (P80)
  1:        3          Input Storage Area
  2:       37          Loc [ St_kW_m2  ]

33:  Average (P71)
  1:        1          Reps
  2:        6          Loc [ Slr_kWm2  ]
```

```
34:  Average (P71)
  1:      1        Reps
  2:      3        Loc [ AirTemp_C ]

35:  Average (P71)
  1:      1        Reps
  2:     36        Loc [ VPD_kPa   ]

36:  Average (P71)
  1:      1        Reps
  2:     41        Loc [ WS_ms     ]

37:  If Flag/Port (P91)
  1:     10        Do if Output Flag is High (Flag 0)
  2:     30        Then Do
```

; Call the ET_o algorithm.

```
38:  Do (P86)
  1:      1        Call Subroutine 1

39:  End (P95)

40:  If time is (P92)
  1:      0        Minutes (Seconds --) into a
  2:     60        Interval (same units as above)
  3:     30        Then Do
```

Sum up hourly ET_o and rainfall values.

```
41:  Z=X+Y (P33)
  1:     26        X Loc [ Rn_Today  ]
  2:     11        Y Loc [ HrRainTtl ]
  3:     26        Z Loc [ Rn_Today  ]

42:  Z=F (P30)
  1:      0        F
  2:      0        Exponent of 10
  3:     11        Z Loc [ HrRainTtl ]

43:  Z=X+Y (P33)
  1:     24        X Loc [ ETo_Today ]
  2:     64        Y Loc [ ETo_in_hr ]
  3:     24        Z Loc [ ETo_Today ]

44:  End (P95)
```

```
45:  Z=X+Y (P33)
  1:      11          X Loc [ HrRainTtl ]
  2:       9          Y Loc [ Rain_inch ]
  3:      11          Z Loc [ HrRainTtl ]

46:  If time is (P92)                                   Collect hourly
  1:       0          Minutes (Seconds --) into a       Final Storage
  2:      60          Interval (same units as above)    data.
  3:      10          Set Output Flag High (Flag 0)

47:  Set Active Storage Area (P80)
  1:       1          Final Storage Area 1
  2:     129          Array ID

48:  Real Time (P77)
  1:    1220          Year,Day,Hour/Minute (midnight = 2400)

49:  Average (P71)
  1:       1          Reps
  2:       4          Loc [ AirTemp_F ]

50:  Sample (P70)
  1:       1          Reps
  2:       5          Loc [ RH        ]

51:  Average (P71)
  1:       1          Reps
  2:      34          Loc [ VP_kPa    ]

52:  Average (P71)
  1:       1          Reps
  2:       6          Loc [ Slr_kWm2  ]

53:  Sample (P70)                                       Collect ETo
  1:       1          Reps                              in inches/hour.
  2:      64          Loc [ ETo_in_hr ]

54:  Wind Vector (P69)
  1:       1          Reps
  2:       0          Samples per Sub-Interval
  3:       0          S, θλ, & σ(θλ)
  4:       7          Wind Speed/East Loc [ WS_mph    ]
  5:       8          Wind Direction/North Loc [ Wind_Dir  ]
```

```
55:  Totalize (P72)
  1:        1          Reps
  2:        9          Loc [ Rain_inch ]

56:  If time is (P92)
  1:        0          Minutes (Seconds --) into a
  2:     1440          Interval (same units as above)
  3:       30          Then Do

57:  Z=X (P31)
  1:       24          X Loc [ ETo_Today ]
  2:       23          Z Loc [ ETo_24hr  ]

58:  Z=F (P30)
  1:        0          F
  2:        0          Exponent of 10
  3:       24          Z Loc [ ETo_Today ]

59:  Z=X (P31)
  1:       26          X Loc [ Rn_Today  ]
  2:       25          Z Loc [ Rain24hr  ]

60:  Z=F (P30)
  1:        0          F
  2:        0          Exponent of 10
  3:       26          Z Loc [ Rn_Today  ]

61:  End (P95)

62:  If time is (P92)
  1:        0          Minutes (Seconds --) into a
  2:     1440          Interval (same units as above)
  3:       10          Set Output Flag High (Flag 0)

63:  Set Active Storage Area (P80)
  1:        3          Input Storage Area
  2:       12          Loc [ 24HMxTmpF ]

64:  Maximum (P73)
  1:        1          Reps
  2:        0          Value Only
  3:        4          Loc [ AirTemp_F ]
```

Move daily ET_o and rainfall values. Set daily running totals back to zero.

```
65:  Minimum (P74)
 1:        1          Reps
 2:        0          Value Only
 3:        4          Loc [ AirTemp_F ]

66:  Average (P71)
 1:        1          Reps
 2:        4          Loc [ AirTemp_F ]

67:  Maximum (P73)
 1:        1          Reps
 2:        0          Value Only
 3:        5          Loc [ RH        ]

68:  Minimum (P74)
 1:        1          Reps
 2:        0          Value Only
 3:        5          Loc [ RH        ]

69:  Maximum (P73)
 1:        1          Reps
 2:        0          Value Only
 3:        7          Loc [ WS_mph    ]

70:  If time is (P92)                                      Collect daily
 1:        0          Minutes (Seconds --) into a          Final Storage
 2:     1440          Interval (same units as above)       values at
 3:       10          Set Output Flag High (Flag 0)        midnight.

71:  Set Active Storage Area (P80)
 1:        1          Final Storage Area 1
 2:      139          Array ID

72:  Real Time (P77)
 1:     1220          Year,Day,Hour/Minute (midnight = 2400)

73:  Average (P71)
 1:        1          Reps
 2:        4          Loc [ AirTemp_F ]

74:  Maximum (P73)
 1:        1          Reps
 2:        0          Value Only
 3:        4          Loc [ AirTemp_F ]
```


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```
75:  Minimum (P74)
 1:        1         Reps
 2:        0         Value Only
 3:        4         Loc [ AirTemp_F ]

76:  Average (P71)
 1:        1         Reps
 2:       34         Loc [ VP_kPa    ]

77:  Maximum (P73)
 1:        1         Reps
 2:        0         Value Only
 3:       34         Loc [ VP_kPa    ]

78:  Minimum (P74)
 1:        1         Reps
 2:        0         Value Only
 3:       34         Loc [ VP_kPa    ]

79:  Average (P71)
 1:        1         Reps
 2:        6         Loc [ Slr_kWm2  ]

80:  Sample (P70)                               Collect daily
 1:        1         Reps                       ETo in
 2:       23         Loc [ ETo_24hr  ]          inches/day.

81:  Maximum (P73)
 1:        1         Reps
 2:        0         Value Only
 3:        7         Loc [ WS_mph    ]

82:  Average (P71)
 1:        1         Reps
 2:        7         Loc [ WS_mph    ]

83:  Totalize (P72)
 1:        1         Reps
 2:        9         Loc [ Rain_inch ]

84:  Maximum (P73)
 1:        1         Reps
 2:        0         Value Only
 3:        1         Loc [ Batt_Volt ]
```


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```
85:  Minimum (P74)
  1:      1         Reps
  2:      0         Value Only
  3:      1         Loc [ Batt_Volt ]

86:  Maximum (P73)
  1:      1         Reps
  2:      0         Value Only
  3:      2         Loc [ CR10Tmp_C ]

87:  Minimum (P74)
  1:      1         Reps
  2:      0         Value Only
  3:      2         Loc [ CR10Tmp_C ]

88:  Maximum (P73)
  1:      1         Reps
  2:      0         Value Only
  3:     28         Loc [ Encl_RH   ]

89:  Minimum (P74)
  1:      1         Reps
  2:      0         Value Only
  3:     28         Loc [ Encl_RH   ]

90:  If Flag/Port (P91)
  1:     10         Do if Output Flag is High (Flag 0)
  2:     30         Then Do

91:  Signature (P19)
  1:     27         Loc [ Signature ]

92:  End (P95)

93:  Sample (P70)
  1:      1         Reps
  2:     27         Loc [ Signature ]

94:  Serial Out (P96)
  1:     71         SM192/SM716/CSM1

*Table 2 Program
  01:       0.0000  Execution Interval (seconds)
```

```
*Table 3 Subroutines

01:  Beginning of Subroutine (P85)                     Compute ETo
  1:        1          Subroutine 1                    using
                                                       Penman-Monteith
                                                       equation.

02:  Z=F (P30)                                         Enter site
  1:      41.78        F                               latitude in
  2:        0          Exponent of 10                  degrees.
  3:       47          Z Loc [ latitude  ]

03:  Z=F (P30)                                         Enter site
  1:        -.45667 F                                  longitudinal
  2:        0          Exponent of 10                  correction
  3:       48          Z Loc [ lngt_cor  ]             (see equation 11).

04:  Z=F (P30)                                         Enter site
  1:   4454            F                               elevation in
  2:        0          Exponent of 10                  feet above sea
  3:       49          Z Loc [ elev_ft   ]             level.

05:  Time (P18)
  1:        2          Hours into current year {maximum 8784)
  2:        0          Mod/By
  3:       42          Loc [ clndr_day ]

06:  Z=X*F (P37)                                       Convert hours
  1:       42          X Loc [ clndr_day ]             to days.
  2:          .04167 F
  3:       42          Z Loc [ clndr_day ]

07:  Z=X*F (P37)                                       Scale days for
  1:       42          X Loc [ clndr_day ]             polynomial.
  2:          .01      F
  3:       65          Z Loc [ day_100   ]
```

```
08:  Polynomial (P55)
  1:        1          Reps
  2:       65          X Loc [ day_100   ]
  3:       43          F(X) Loc [ sindec    ]
  4:        -.37726    C0
  5:        -.10564    C1
  6:        1.2458     C2
  7:        -.75478    C3
  8:         .13627    C4
  9:        -.00572    C5

09:  If (X<=>F) (P89)
  1:       42          X Loc [ clndr_day ]
  2:        3          >=
  3:      180          F
  4:       30          Then Do

10:  Z=X+F (P34)
  1:       65          X Loc [ day_100   ]
  2:       -1.8        F
  3:       66          Z Loc [ eq_of_tim ]

11  Polynomial (P55)                                  Equation of
  1:        1          Reps                           time
  2:       66          X Loc [ eq_of_tim ]            polynomial
  3:       66          F(X) Loc [ eq_of_tim ]         for last half
  4:        -.05039    C0                             of the year.
  5:        -.33954    C1
  6:         .04084    C2
  7:        1.8928     C3
  8:       -1.7619     C4
  9:         .4224     C5

12:  Else (P94)

13:  Polynomial (P55)                                 Equation of
  1:        1          Reps                           time
  2:       65          X Loc [ day_100   ]            polynomial
  3:       66          F(X) Loc [ eq_of_tim ]         for first half
  4:        -.04056    C0                             of the year.
  5:        -.74503    C1
  6:         .08823    C2
  7:        2.0516     C3
  8:       -1.8111     C4
  9:         .42832    C5
```


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```
14:  End (P95)

15:  Z=X*Y (P36)
 1:      43         X Loc [ sindec    ]
 2:      43         Y Loc [ sindec    ]
 3:      44         Z Loc [ cosdec    ]

16:  Z=X*F (P37)
 1:      44         X Loc [ cosdec    ]
 2:      -1         F
            3:      44  Z Loc [ cosdec    ]

17:  Z=Z+1 (P32)
 1:      44         Z Loc [ cosdec    ]

18:  Z=SQRT(X) (P39)                          cos d =
 1:      44         X Loc [ cosdec    ]       (1-(sin d)^2)^1/2
 2:      44         Z Loc [ cosdec    ]

19:  Z=SIN(X) (P48)
 1:      47         X Loc [ latitude  ]
 2:      45         Z Loc [ sind_sinl ]

20:  Z=X*Y (P36)                              Sine of
 1:      43         X Loc [ sindec    ]       latitude.
 2:      45         Y Loc [ sind_sinl ]
 3:      45         Z Loc [ sind_sinl ]

21:  Z=X+F (P34)
 1:      47         X Loc [ latitude  ]
 2:      90         F
 3:      46         Z Loc [ cosd_cosl ]

22:  Z=SIN(X) (P48)                           Cosine of
 1:      46         X Loc [ cosd_cosl ]       latitude.
 2:      46         Z Loc [ cosd_cosl ]

23:  Z=X*Y (P36)
 1:      44         X Loc [ cosdec    ]
 2:      46         Y Loc [ cosd_cosl ]
 3:      46         Z Loc [ cosd_cosl ]
```

```
24:  Time (P18)
 1:      1         Minutes into current day (maximum 1440)
 2:      0         Mod/By
 3:     50         Loc [ t_to      ]

25:  Z=X*F (P37)                                    Convert to
 1:     50         X Loc [ t_to      ]              hours.
 2:        .01667  F
 3:     50         Z Loc [ t_to      ]

26:  Z=X+F (P34)                                    Subtract an
 1:     50         X Loc [ t_to      ]              extra half
 2:    -12.5       F                                hour to get
 3:     50         Z Loc [ t_to      ]              the time at the
                                                    middle of the
27:  Z=X+Y (P33)                                    averaging
 1:     50         X Loc [ t_to      ]              interval.
 2:     48         Y Loc [ lngt_cor  ]
 3:     50         Z Loc [ t_to      ]

28:  Z=X+Y (P33)
 1:     50         X Loc [ t_to      ]
 2:     66         Y Loc [ eq_of_tim ]
 3:     50         Z Loc [ t_to      ]

29:  Z=X*F (P37)                                    Convert to
 1:     50         X Loc [ t_to      ]              degrees.
 2:     15         F
 3:     51         Z Loc [ sin_elev  ]

30:  Z=X+F (P34)
 1:     51         X Loc [ sin_elev  ]
 2:     90         F
 3:     51         Z Loc [ sin_elev  ]

31  Z=SIN(X) (P48)
 1:     51         X Loc [ sin_elev  ]
 2:     51         Z Loc [ sin_elev  ]

32:  Z=X*Y (P36)
 1:     51         X Loc [ sin_elev  ]
 2:     46         Y Loc [ cosd_cosl ]
 3:     51         Z Loc [ sin_elev  ]
```

```
33:  Z=X+Y (P33)
  1:      51         X Loc [ sin_elev  ]
  2:      45         Y Loc [ sind_sinl ]
  3:      51         Z Loc [ sin_elev  ]
```

$\sin\phi =$ $(\sin d)(\sin l) +$ $(\cos d)(\cos l)$ $(\cos(15x(t\text{-}t_o)))$

```
34:  If (X<=>F) (P89)
  1:      51         X Loc [ sin_elev  ]
  2:       4         <
  3:       0         F
  4:      30         Then Do

35:  Z=F (P30)
  1:       0         F
  2:       0         Exponent of 10
  3:      51         Z Loc [ sin_elev  ]

36:  End (P95)

37:  Z=X*F (P37)
  1:      51         X Loc [ sin_elev  ]
  2:       1.36      F
  3:      52         Z Loc [ So_kW_m2  ]
```

$S_o = 1.36 * \sin\phi$

```
38:  If (X<=>F) (P89)
  1:      51         X Loc [ sin_elev  ]
  2:       3         >=
  3:        .3       F
  4:      30         Then Do

39:  Z=X/Y (P38)
  1:      37         X Loc [ St_kW_m2  ]
  2:      52         Y Loc [ So_kW_m2  ]
  3:      53         Z Loc [ funcSt_So ]

40:  If (X<=>F) (P89)
  1:      53         X Loc [ funcSt_So ]
  2:       3         >=
  3:        .8       F
  4:      30         Then Do
```

Limit range of S_t/S_o to 0.2-0.8

```
41:  Z=F (P30)
  1:        .8       F
  2:       0         Exponent of 10
  3:      53         Z Loc [ funcSt_So ]
```

```
42:  End (P95)

43:  If (X<=>F) (P89)
 1:      53          X Loc [ funcSt_So ]
 2:       4          <
 3:        .2        F
 4:      30          Then Do

44:  Z=F (P30)
 1:        .2        F
 2:       0          Exponent of 10
 3:      53          Z Loc [ funcSt_So ]

45:  End (P95)

46:  Z=X*F (P37)
 1:      53          X Loc [ funcSt_So ]
 2:       7.9        F
 3:      53          Z Loc [ funcSt_So ]

47:  Z=EXP(X) (P41)
 1:      53          X Loc [ funcSt_So ]
 2:      53          Z Loc [ funcSt_So ]

48:  Z=X*F (P37)
 1:      53          X Loc [ funcSt_So ]
 2:        .034      F
 3:      53          Z Loc [ funcSt_So ]

49:  Z=Z+1 (P32)
 1:      53          Z Loc [ funcSt_So ]

50:  Z=1/X (P42)
 1:      53          X Loc [ funcSt_So ]
 2:      53          Z Loc [ funcSt_So ]

51:  Z=X*F (P37)
 1:      53          X Loc [ funcSt_So ]
 2:      -1          F
 3:      53          Z Loc [ funcSt_So ]

52:  Z=X+F (P34)
 1:      53          X Loc [ funcSt_So ]
 2:       1          F
 3:      53          Z Loc [ funcSt_So ]
```

Cloud effect on isothermal long wave.

```
53:  End (P95)

54:  Z=X*F (P37)
  1:      38          X Loc [ AvgTempC  ]
  2:        .0003     F
  3:      54          Z Loc [ Lni_clear ]

55:  Z=X+F (P34)
  1:      54          X Loc [ Lni_clear ]
  2:       -.107      F
  3:      54          Z Loc [ Lni_clear ]

56:  Z=X*Y (P36)
  1:      53          X Loc [ funcSt_So ]
  2:      54          Y Loc [ Lni_clear ]
  3:      55          Z Loc [ Lni       ]

57:  Z=X*F (P37)
  1:      37          X Loc [ St_kW_m2  ]
  2:        .77       F
  3:      56          Z Loc [ Rn_G      ]

58:  Z=X+Y (P33)
  1:      56          X Loc [ Rn_G      ]
  2:      55          Y Loc [ Lni       ]
  3:      56          Z Loc [ Rn_G      ]

59:  If (X<=>F) (P89)
  1:      37          X Loc [ St_kW_m2  ]
  2:       3          >=
  3:        .01       F
  4:      30          Then Do

60:  Z=X*F (P37)
  1:      56          X Loc [ Rn_G      ]
  2:        .9        F
  3:      56          Z Loc [ Rn_G      ]

61:  Z=F (P30)
  1:      70          F
  2:       0          Exponent of 10
  3:      57          Z Loc [ rv        ]
```

Unsworth-Monteith formula: L_{nic} = $(0.0003)(T_a)$-0.107 W/m^2

Assume reference crop albedo is 0.23, $(a_s)(S_t)$ = 0.77

If S_t>10 W/m^2 then r_c is 70 s/m and G = (0.1) (R_n) else set r_c to 700 s/m for night and G = (0.5) (R_n).

Assume G is (0.1)(R_n) for reference crop during the day or (0.5) (R_n) at night.

```
62:  Else (P94)

63:  Z=X*F (P37)
  1:      56        X Loc [ Rn_G      ]
  2:         .5     F
  3:      56        Z Loc [ Rn_G      ]

64:  Z=F (P30)
  1:     700        F
  2:       0        Exponent of 10
  3:      57        Z Loc [ rv        ]

65:  End (P95)

66:  Z=1/X (P42)
  1:      40        X Loc [ AvgWS_ms  ]
  2:      67        Z Loc [ ra        ]

67:  Z=X*F (P37)                                    ra = 209/u2
  1:      67        X Loc [ ra        ]             (2 meters) or
  2:     240        F                               240/u3
  3:      67        Z Loc [ ra        ]             (3 meters)

68:  Z=X+Y (P33)                                    Add boundary
  1:      57        X Loc [ rv        ]             layer
  2:      67        Y Loc [ ra        ]             resistance.
  3:      57        Z Loc [ rv        ]

69:  Z=X*F (P37)
  1:      49        X Loc [ elev_ft   ]
  2:         .001   F
  3:      59        Z Loc [ GmmaPrime ]

70:  Z=X*F (P37)
  1:      59        X Loc [ GmmaPrime ]
  2:        -.03588 F
  3:      59        Z Loc [ GmmaPrime ]

71:  Z=EXP(X) (P41)                                 P/Po = exp
  1:      59        X Loc [ GmmaPrime ]             (-altitude(feet)/
  2:      59        Z Loc [ GmmaPrime ]             27870)
```

```
72:  Z=X*F (P37)                                      γ at sea level
  1:      59          X Loc [ GmmaPrime ]          and 20° Celsius
  2:      67.3        F                            is 67.3 Pa.
  3:      59          Z Loc [ GmmaPrime ]          This multiplies
                                                   the altitude
73:  Z=X*Y (P36)                                      correction.
  1:      59          X Loc [ GmmaPrime ]
  2:      57          Y Loc [ rv        ]
  3:      59          Z Loc [ GmmaPrime ]

74:  Z=X/Y (P38)                                      γ* = γ*•rv/ra
  1:      59          X Loc [ GmmaPrime ]
  2:      67          Y Loc [ ra        ]
  3:      59          Z Loc [ GmmaPrime ]

75:  If (X<=>F) (P89)
  1:      38          X Loc [ AvgTempC  ]
  2:       4          <
  3:      -5          F
  4:      30          Then Do

76:  Z=F (P30)
  1:      -5          F
  2:       0          Exponent of 10
  3:      60          Z Loc [ delta     ]

77:  Else (P94)

78:  Z=X (P31)
  1:      38          X Loc [ AvgTempC  ]
  2:      60          Z Loc [ delta     ]

79:  End (P95)

80:  Polynomial (P55)                                 Calculate Δ
  1:       1          Reps                         by using a
  2:      60          X Loc [ delta     ]          polynomial.
  3:      60          F(X) Loc [ delta     ]       Result is
  4:      45.3        C0                           Pa/°C.
  5:        2.97      C1
  6:          .0549   C2
  7:          .00223  C3
  8:       0          C4
  9:       0          C5
```

```
81:  Z=X+Y (P33)
 1:      60          X Loc [ delta      ]
 2:      59          Y Loc [ GmmaPrime ]
 3:      61          Z Loc [ Erad_mm_h ]

82:  Z=X/Y (P38)                                   γ*/(Δ + γ*)
 1:      59          X Loc [ GmmaPrime ]
 2:      61          Y Loc [ Erad_mm_h ]
 3:      62          Z Loc [ Eaer_mm_h ]

83:  Z=X/Y (P38)                                   Δ/(Δ + γ*)
 1:      60          X Loc [ delta      ]
 2:      61          Y Loc [ Erad_mm_h ]
 3:      61          Z Loc [ Erad_mm_h ]

84:  Z=X*Y (P36)
 1:      61          X Loc [ Erad_mm_h ]
 2:      56          Y Loc [ Rn_G       ]
 3:      61          Z Loc [ Erad_mm_h ]

85:  Z=X*F (P37)
 1:      61          X Loc [ Erad_mm_h ]
 2:        1.47      F
 3:      61          Z Loc [ Erad_mm_h ]

86:  Z=X*F (P37)                                   Convert to
 1:      62          X Loc [ Eaer_mm_h ]           mm/hr.
 2:      26.6        F
 3:      62          Z Loc [ Eaer_mm_h ]

87:  Z=X*Y (P36)
 1:      62          X Loc [ Eaer_mm_h ]
 2:      39          Y Loc [ Avg_VPD   ]
 3:      62          Z Loc [ Eaer_mm_h ]

88:  Z=X/Y (P38)
 1:      62          X Loc [ Eaer_mm_h ]
 2:      57          Y Loc [ rv         ]
 3:      62          Z Loc [ Eaer_mm_h ]

89:  Z=X+Y (P33)
 1:      61          X Loc [ Erad_mm_h ]
 2:      62          Y Loc [ Eaer_mm_h ]
 3:      63          Z Loc [ ETo_mm_hr ]
```

```
90:  If (X<=>F) (P89)
  1:      63          X Loc [ ETo_mm_hr ]
  2:       4          <
  3:       0          F
  4:      30          Then Do

91:  Z=F (P30)                                            ETo must be
  1:       0          F                                   > = 0.
  2:       0          Exponent of 10
  3:      63          Z Loc [ ETo_mm_hr ]

92:  End (P95)

93:  Z=X*F (P37)                                          Converts ETo
  1:      63          X Loc [ ETo_mm_hr ]                 mm/hr to
  2:         .03937   F                                   inches/hr.
  3:      64          Z Loc [ ETo_in_hr ]

94:  End (P95)

End Program

-Input Locations-
1 Batt_Volt
2 CR10Tmp_C
3 AirTemp_C
4 AirTemp_F
5 RH
6 Slr_kWm2
7 WS_mph
8 Wind_Dir
9 Rain_inch
10 _________
11 HrRainTtl
12 24HMxTmpF
13 24HMnTmpF
14 24HAvTmpF
15 24HMaxRH
16 24HMinRH
17 24HMaxWS
18 _________
19 _________
20 _________
21 _________
22 _________
```


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23 ETo_24hr
24 ETo_Today
25 Rain24hr
26 Rn_Today
27 Signature
28 Encl_RH
29 __________
30 __________
31 __________
32 __________
33 __________
34 VP_kPa
35 Sat_VP
36 VPD_kPa
37 St_kW_m2
38 AvgTempC
39 Avg_VPD
40 AvgWS_ms
41 WS_ms
42 clndr_day
43 sindec
44 cosdec
45 sind_sinl
46 cosd_cosl
47 latitude
48 lngt_cor
49 elev_ft
50 t_to
51 sin_elev
52 So_kW_m2
53 funcSt_So
54 Lni_clear
55 Lni
56 Rn_G
57 rv
58 __________
59 GmmaPrime
60 delta
61 Erad_mm_h
62 Eaer_mm_h
63 ETo_mm_hr
64 ETo_in_hr
65 day_100
66 eq_of_tim
67 ra

68 __________
69 __________
70 __________
129 __________ 0 0 0
139 __________ 0 0 0
-Program Security-
0000
0000
0000
-Mode 4-
-Final Storage Area 2-
0
-CR10X ID-
0
-CR10X Power Up-
3

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