DERIVED VARIABLES IN DAVIS WEATHER PRODUCTS

Application Note **28**

The following parameters do not have any sensors or circuitry. They are calculated from measured variables. Any conditions that affect the functions of the measurements that are used to calculate these variables will affect the readings of these variables. This includes the Vantage Pro2™, Vantage VUE, and Vantage Pro® and Setup Screen settings. In each case unless otherwise noted, the software uses the exact formula and the console uses a lookup table that closely approximates the formula.

WIND CHILL

Parameters Used: Outside Air Temperature and Wind Speed

What is it?
Wind chill takes into account how the speed of the wind affects our perception of the air temperature. Our bodies warm the surrounding air molecules by transferring heat from the skin. If there's no air movement, this insulating layer of warm air molecules stays next to the body and offers some protection from cooler air molecules. However, wind sweeps that comfy warm air surrounding the body away. The faster the wind blows, the faster heat is carried away and the colder the environment feels.

The formula below was adopted by both Environment Canada and the U.S. National Weather Service to ensure a uniform wind chill standard in North America. The formula is supposed to more closely emulate the response of the human body when exposed to conditions of wind and cold than the previous formula did:

$$35.74 + 0.6215T - 35.75 * (V^{0.16}) + 0.4275T * (V^{0.16})$$

This relationship takes into account the fact that wind speeds are measured "officially" at 10 meters (33 feet) above the ground, but the human is typically only 5 to 6 feet (2 meters) above the ground. So, anemometers still need to be mounted as high as possible (e.g., rooftop mast) to register comparable wind speed readings and wind chill values. See Application Note 30 for siting recommendations and guidelines.

This newer version of the formula addresses the fact that the latest National Weather Service (NWS) formula was not designed for use above 40°F. The result of the straight NWS implementation was little or no chilling effect at mild temperatures. This updated version provides for reasonable chilling effect at mild temperatures based on the effects determined by Steadman (1979) (see THSW Index section), but as with the new NWS formula, no upper limit where chilling has no additional effect. No chilling affect occurs at wind speeds of 0 mph or temperatures at or above 93.2°F (34°C). As per Steadman (1979), 93.2 F (34°C) is the average temperature of skin at mild temperatures, thus temperatures above this value will actually create an apparent warming effect (see THSW Index section).

The Vantage Pro2, Vantage VUE, and Vantage Pro consoles use the "10-minute average wind speed" to determine wind chill, which is updated once per minute. When 10-minute of wind speed data is unavailable, it uses a running average until 10-minutes worth of data is collected. The WeatherLink® software uses the 10-minute average wind speed also. If it is unavailable, it uses the current wind speed (which updates every 2.5 to 3 seconds).

The reason an average wind speed is employed in the Vantage Pro2, Vantage VUE and Vantage Pro to calculate wind chill is as follows: The human body has a high heat capacity, thus wind gusts have no effect on the body's thermal equilibrium. So, an average wind speed provides a more accurate representation of the body's response than an instantaneous reading. Also, "official" weather reports (from which wind chill is calculated) provide average wind speed, so using an average wind speed more closely matches the results that are seen in weather reports.

REFERENCES

"Media Guide to NWS Products and Services", National Weather Service Forecast Office, Monterey, CA, 1995.

"New Wind Chill Temperature Index", Office of Climate, Water and Weather Services, Washington, DC, 2001.

Siple, P. and C. Passel, 1945. Measurements of Dry Atmospheric Cooling in Subfreezing Temperatures. *Proc. Amer. Philos. Soc.*

Steadman, R.G., 1979: The Assessment of Sultriness, Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. *Journal of Applied Meteorology, July 1979*

HEAT INDEX

Parameters Used: Outside Air Temperature and Outside Humidity

What is it?
Heat Index uses temperature and relative humidity to determine how hot the air actually "feels." When humidity is low, the apparent temperature will be lower than the air temperature, since perspiration evaporates rapidly to cool the body. However, when humidity is high (i.e., the air is saturated with water vapor) the apparent temperature "feels" higher than the actual air temperature, because perspiration evaporates more slowly.

Formulas:
Heat Index is based upon a lookup table presented by Steadman (1979) and loosely derived from the methodology outlined by Steadman (1998). Thus, air temperatures below 50°F follow this 1998 procedure. Air temperatures above 68°F follow his procedure outlined in 1979 (since the US NWS continues to use this). Davis has made a smooth transition between the two methods between 50°F and 68°F.

The formula Davis uses is also used by the US National Weather Service. Heat Index can also be used to determine indoor comfort levels.

REFERENCES

Steadman, R.G., 1979: The Assessment of Sultriness, Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. *Journal of Applied Meteorology, July 1979*

"Media Guide to NWS Products and Services", National Weather Service Forecast Office, Monterey, CA, 1995.

Quayle, R.G. and Steadman, R.G., 1998: The Steadman Wind Chill: An Improvement over Present Scales. *Weather and Forecasting, December 1998*

DEWPOINT

Parameters Used: Outside Air Temperature and Outside Humidity

What is it?
Dewpoint is the temperature to which air must be cooled for saturation (100% relative humidity) to occur, providing there is no change in water content. The dewpoint is an important measurement used to predict the formation of dew, frost, and fog. If dewpoint and temperature are close together in the late afternoon when the air begins to turn colder, fog is likely during the night. Dewpoint is also a good indicator of the air's actual water vapor content, unlike relative humidity, which is air temperature dependent. High dewpoint indicates high vapor content; low dewpoint indicates low vapor content. In addition, a high dewpoint indicates a better chance of rain and severe thunderstorms. Dewpoint can be used to predict the minimum overnight temperature. Provided no new fronts are expected overnight and the afternoon Relative Humidity >=50%, the afternoon's dewpoint gives an idea of what minimum temperature to expect overnight. Since condensation occurs when the air temperature reaches the dewpoint, and condensation releases heat into the air, reaching the dewpoint halts the cooling process.

Formula:
The following method is used to calculate dewpoint:

$v = RH*0.01*6.112 * \exp[(17.62*T)/(T + 243.12)]$,

this equation will provide the vapor pressure value (in pressure units) where T is the air temperature in C and RH is the relative humidity.

Now dewpoint, Td, can be found:

Numerator = $243.12*(\ln v) - 440.1$

Denominator = $19.43 - \ln v$

Td = Numerator/Denominator

This equation is an approximation of the Goff & Gratch equation, which is extremely complex. This equation is one recommended by the World Meteorological Organization for saturation of air with respect to water.

REFERENCES

"Guide to Meteorological Instruments and Methods of Observation". World Meteorological Organization, Geneva, Switzerland, 6th Ed. 1996.

"Smithsonian Meteorological Tables". Smithsonian Institution Press, Washington, DC, 4th Ed. 1968.

THSW INDEX

Parameters Used: Temperature, Humidity, Solar Radiation, Wind Speed, Latitude & Longitude, Time and Date

What is it:
Like Heat Index, the THSW Index uses humidity and temperature to calculate an apparent temperature. In addition, THSW incorporates the heating effects of solar radiation and the cooling effects of wind (like wind chill) on our perception of temperature.

Formula:
The formula was developed by Steadman (1979). The following describes the series of formulas used to determine the THSW or Temperature-Humidity-Sun-Wind Index.

This Index is calculated by adding a series of successive terms. Each term represents one of the three parameters: (Humidity, Sun & Wind). The humidity term serves as the base from which increments for sun and wind effects are added. (THSW Index is not available on Vantage VUE).

HUMIDITY FACTOR

The first term is humidity. This term is determined in the same manner as the Heat Index. This term serves as a base number to which increments of wind and sun are added to come up with the final THSW Index temperature.

WIND FACTOR

The second term is wind. This term is determined in part by a lookup table and in part by the wind chill calculation. With this in mind, the following criterion apply:

- At 0 mph, this term is equal to zero.
- For temperatures at or above 144°F, this term is set equal to zero. This is based on a best-fit regression of the Steadman 1979 wind table.
- For temperatures below 50°F, the wind chill depression (temperature – wind chill) is used.

The resulting value is the wind term, which will be added to the humidity term and subsequently the sun term as indicated below.

Note: The WeatherLink software (versions 5.2 and later) has a variable which does not include the sun term in its calculation. It is the "THW Index" or Temperature-Humidity-Wind Index. This value indicates the "apparent" temperature in the shade due to these factors.

SUN FACTOR

The third term is sun. This term, *Qg*, is actually a combination of four terms (direct incoming solar, indirect incoming solar, terrestrial, and sky radiation). The term depends upon wind speed to determine how strong an effect it is. The value is limited to between −20 and +130 W/m^2.

REFERENCES

Steadman, R.G., 1979: The Assessment of Sultriness, Part II: Effects of Wind, Extra Radiation and Barometric Pressure on Apparent Temperature. *Journal of Applied Meteorology, July 1979.*

"Media Guide to NWS Products and Services", National Weather Service Forecast Office, Monterey, CA, 1995.

Quayle, R.G. and Steadman, R.G., 1998: The Steadman Wind Chill: An Improvement over Present Scales. *Weather and Forecasting, December 1998*

BAROMETRIC PRESSURE

What is it?
The weight of the air that makes up our atmosphere exerts a pressure on the surface of the earth. This pressure is known as atmospheric pressure. Generally, the more air above an area, the higher the atmospheric pressure, this, in turn, means that atmospheric pressure changes with altitude. For example, atmospheric pressure is greater at sea-level than on a mountaintop. To compensate for this difference and facilitate comparison between locations with different altitudes, atmospheric pressure is generally adjusted to the equivalent sea-level pressure. This adjusted pressure is known as barometric pressure. In reality, the Vantage Pro2, Vantage VUE and Vantage Pro measure atmospheric pressure. When entering the location's altitude in Setup Mode, these systems calculate the necessary correction factor to consistently translate atmospheric pressure into barometric pressure.

Barometric pressure also changes with local weather conditions, making barometric pressure an extremely important and useful weather forecasting tool. High pressure zones are generally associated with fair weather while low pressure zones are generally associated with poor weather. For forecasting purposes, however, the absolute barometric pressure value is generally less important than the change in barometric pressure. In general, rising pressure indicates improving weather conditions while falling pressure indicates deteriorating weather conditions.

The following section applies to Vantage Pro2, Vantage VUE and Vantage Pro systems only. The method described here is called the "NOAA" bar reduction selection on the Vantage VUE.

Parameters Used: Outside Air Temperature, Outside Humidity, Elevation, Atmospheric Pressure

Formula:
Simply,

$P_{SL} = P_S * (R)$,

where P_{SL} is sea level pressure, P_S is the unadjusted reading sensed by the Davis barometer, and R is the reduction ratio, which is determined as follows:

First, Tv (virtual temperature in the "fictitious column of air" extending down to sea-level) can be determined as follows. The result is in degrees Rankin, which is similar to Kelvin except it uses Fahrenheit scale divisions rather than Celsius scale divisions:

$Tv = T + 460 + L + C$,

where T is the average between the current outdoor temperature and the temperature 12 hours ago (in Fahrenheit) in whole degrees. L is the typical lapse rate, or decrease in temperature with height (of the "fictitious column of air"), as calculated by:

$L = 11\ Z/8000$,

where L is a constant value with units in °F. Z is elevation, which must be entered in feet.

The current dewpoint value and the station elevation are necessary to compute C. C is the correction for the humidity in the "fictitious column of air". It is determined from a lookup table. The table consists of dewpoints in °F every 4°F and elevations in feet every 1500 feet. Linear interpolation is performed to obtain the correct reduced pressure value. For dewpoints below –76°F, C = 0; for dewpoints above 92°F, a dewpoint of 92°F is assumed.

Now, *Tv* can be determined. From this, the following can be computed:

Exponent = [*Z*/(122.8943111**Tv*)]

Once this exponent is computed, R can be computed from the following:

R = 10^[Exponent].

Thus, $P_{SL} = P_S * (R)$ can be calculated. Pressure can be in any units (*R* is dimensionless) and still yield the correct value.

This procedure is designed to produce the correct reduced sea-level pressure as displayed. This requires the user to know their elevation to at least ±10 feet to be accurate to every .01" Hg or ±3 feet to be accurate to every 0.1 mb/hPa.

This is a simplified version of the official U.S. version in place now. The accepted method is to use lookup tables of ratio reduction values keyed to station temperature. These are based on station climatology. These values are unavailable for every possible location where a Davis user may have a station, thus this approach is not suitable.

It should be noted that if a sensor's pressure readings require adjustment, the user can adjust either the uncorrected or the final reading to match the user's reference, as appropriate. If the user chooses to measure uncorrected atmospheric pressure or use another reduction method, they should set their elevation to zero, or on a Vantage VUE, they can also use the "NONE" selection for bar reduction. Subsequently, output data using the WeatherLink can be read by or exported to another application and converted as desired.

The calibration of the sensor is a separate one-time function performed on the unit during the manufacturing process. It is a completely independent operation from the calculation the Vantage Pro2, Vantage VUE and Vantage Pro console makes to display a reading corrected to sea-level. The calibration is done to ensure the sensor reads uncorrected or raw atmospheric pressure (not barometric pressure) properly. Any properly functioning unit will read the uncorrected atmospheric pressure within specifications. However, limits in the displayable range of the bar value may prevent the user from setting an incorrect elevation for their location. That is, a user at sea-level, may see a dashed reading if they set their unit to 5000' elevation or vice-versa. So, the best way to tell if a Vantage Pro(2) unit is functioning properly, is:

- use a reference that has been adjusted to indicate sea-level pressure and set the console to the proper elevation or
- use a reference that is reading the raw, uncorrected atmospheric pressure and set the console elevation to zero

and verify that these readings are comparable. The Vantage VUE console will display both corrected and uncorrected readings in the Weather Center, so it is not necessary to change the settings to view different values. Additionally, the Vantage VUE shows Altimeter Setting in the same location, which can also be used for verification if a nearby Altimeter value is available (see below).

ALTIMETER SETTING and CWOP

The CWOP program in NOAA prefers to receive altimeter setting data rather than barometric pressure. This feature in WeatherLink 5.7 automatically calculates the correct altimeter setting using the user-specified elevation. Monitor II and Perception II users should set their barometer reading to match the altimeter setting of the nearest National Weather Service (NWS) weather station. Simply enter your zip code on the NWS home page to get the nearest observation. This is usually found at the "3 Day History" (detailed observation section) link under Current Conditions section. http://www.nws.noaa.gov/ . For users outside the United States, contact your country's national meteorological service.

Altimeter Formula, A:

$A = (P^N + K*Z)^(1/N)$, where P is the raw station pressure (in. Hg), $N = 0.1903$, $K = 1.313E -5$, Z is elevation (feet).

REFERENCE

"Smithsonian Meteorological Tables". Smithsonian Institution Press, Washington, DC, 4th Ed. 1968.

"Federal Standard Algorithms for Automated Weather Observing Systems used for Aviation Purposes". Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, DC, 1988

RAINFALL

RAINFALL TOTAL

Davis systems come equipped with a 0.01” or 0.2 mm option for the rain. The Vantage Pro(2) and Vantage VUE are pre-configured for the type of rain collector appropriate for your region. One of the setup-screens allows for this setting to be changed if there is a need.

0.01” rain collectors are designed to be used with an inch unit display setting. 0.2 mm rain collectors are designed to be used with a millimeter (mm) display setting. Most Vantage Pro(2) and Vantage Vue consoles come pre-set to the display setting that matches the rain collector type that the system is equipped with.

RAINFALL RATE

Parameters Used: Rain Total (Rain rate is a measured variable in the sense that it is measured by the ISS and transmitted to the display console, whereas all other calculated variables are determined by the console from data received from the ISS.)

Formula:

Under normal conditions, rain rate data is sent with a nominal interval of 10 to 12 seconds. Every time a rain tip or click occurs, a new rain rate value is computed (from the timer values) and the rate timers are reset to zero.

Rain rate is calculated based on the time between successive tips of the rain collector. The rain rate value is the highest rate since the last transmitted rain rate data packet. (Under most conditions, however, a rain tip will not occur every 10 to 12 seconds.)

If there have been no rain tips since the last rain rate data transmission, then the rain rate based on the time since that last tip is indicated. This results in slowly decaying rate values as a rainstorm ends, instead of showing a rain rate which abruptly drops to zero. This results in a more realistic representation of the actual rain event.

If this time exceeds roughly 15 minutes, then the rain rate value is reset to zero. This period of time was chosen because 15 minutes is defined by the U.S. National Weather Service as intervening time upon which one rain "event" is considered separate from another rain "event". This is also the shortest period of time that the Umbrella will be seen on the display console after the onset of rain.

REFERENCES

"Surface Weather Observations and Reports ". Office of the Federal Coordinator for Meteorological Services and Supporting Research, Washington, DC, 1998

MOON PHASE (Vantage Pro2, Vantage VUE and Vantage Pro, and all WeatherLink 5.X versions and later)

Parameters Used: Latitude, Longitude, Time and Date, Time Zone, Daylight Savings Time Setting

Sufficient accuracy is obtained from the following formula for i, the phase angle:

$$i = 180° - D - 6.289° \sin M' + 2.1° \sin M - 1.274° \sin (2D - M') - 0.658° \sin 2D$$

where
- D is the mean elongation of the moon (the maximum angular distance between the earth and the moon)
- M' is the moon's mean anomaly (angular distance, measured from where the moon is closest to the earth in its orbit, if it moved around the earth at a constant angular velocity)
- M is the sun's mean anomaly (angular distance, measured from where the earth is closest to the sun in its orbit, if it moved around the earth at a constant angular velocity)

and the terms in the equation provide increasing amounts of mean accuracy to calculate the phase angle as follows (hr:min):
- D = 20:57
- $6.289° \sin M'$ = 8:35
- $2.1° \sin M$ = 4:26
- $1.274° \sin (2D - M')$ = 1:56
- $0.658° \sin 2D$ = 0:38

Note: these equations assume that the sun and moon both revolve around the earth, for simplicity. However, when addressing the positions in orbit, it is actually the earth revolving around the sun, so this should be understood when trying to understand the physical meaning described in the definitions.

The equations for D, M' and M are as follows:

$D = 297.8501921 + 12.19074911 * days$
$M' = 134.9633964 + 13.06499295 * days$
$M = 357.52911 + 0.985600281 * days$,

Where *days* (in days and fractions of days) is the number of days since Jan 1st, 2000 at 12:00 UTC

Local time needs to be converted to UTC in order to be used in the formulas:

UTC = Local Time - Time Zone Offset (including adding one hour for daylight savings if and when in use)

The phase angle is modified so that it can be used to determine whether the moon is waxing (illuminated portion increasing in size) or waning (decreasing in size):

If $i >= 180°$, then $k = 1 - (k / 2)$

Now, the phase angle can be used to determine which phase the moon is in:

$i = (i * 8) + 0.5$

The result is interpreted as follows:
0 = New Moon, 1 = Waxing Crescent, 2 = First Quarter, 3 = Waxing Gibbous, 4 = Full Moon,
5 = Waning Gibbous, 6 = Last Quarter, 7 = Waning Crescent

WEATHERLINK BULLETIN GRAPHIC

k is the fraction of the moon's disk that is illuminated. It is used to draw the moon phase icon in the Bulletin.

$k = (1 + \cos i)/ 2$

k is a number between zero and one that indicates how much of the moon's disk should be drawn as lit. It indicates the "terminator's" (boundary between light and dark face) position on the observed face of the moon.

k can also be interpreted as listed below
0.00 = New Moon
0.25 = First Quarter
0.50 = Full Moon
0.75 = Last Quarter

REFERENCE

Meeus, Jean: "Astronomical Algorithms". Willman-Bell, Richmond, VA, 2nd Ed. 1998.

DESCRIPTION OF EVAPOTRANSPIRATION (ET), REFERENCE ET, AND THE CROP COEFFICIENT

Evapotranspiration (ET) is the amount of water that moves from the ground (and plants on the ground) to the atmosphere through both evaporation and transpiration. It is primarily important to people who are monitoring plant growth and associated water usage.

Measuring actual ET for a given location requires the measurement of weather variables at different heights at the same location and is beyond the capabilities of the current Davis weather stations. Instead, a single set of weather data measurements (described in detail below) are used to calculate a Reference ET (ET_o). ET_o is the amount of ET that is expected at a location with specified reference conditions under the actual weather conditions. The two most common reference conditions used for agricultural purposes are the grass reference – well watered grass that completely shades the ground, is uniformly clipped to a few inches in height – and the alfalfa reference – similar to the grass reference with alfalfa instead of grass, and a different height. The Davis ET calculations all calculate ET_o for a grass reference.

To determine actual ET from a reference ET_o, multiply the ET_o by a crop coefficient (K_c). The crop coefficient accounts for the type of plant, the maturity of the plant, and may include local factors such as soil type. Davis Instruments does not supply crop coefficients. It is up to the individual user to determine what K_c is appropriate. See below for a list of some sources. It is very important, when selecting K_c to make sure that the coefficient is for use with a grass reference. Do not use coefficients that were derived from alfalfa referenced ET_o.

THE DAVIS ET_O CALCULATIONS

Hourly ET values are calculated from hourly averages of weather variables.

Note: a Vantage VUE console must be listening to a Vantage Pro2 ISS equipped with a solar radiation sensor to calculate and display ET.

DATA SAMPLING AND VARIABLES REQUIRED FOR CALCULATION

The temperature is calculated in tenths of a degree F, the humidity is calculated in tenths of a percent, wind speed is calculated in miles per hour, solar radiation is calculated in watts per square meter, and atmospheric pressure is read in thousandths of an inch of mercury. All arithmetic is in integers. Values that use fractions are represented by multiplying by an appropriate value. The formulas given below that use functions more complicated than addition, subtraction, multiplication, and division are calculated with table lookups with linear interpolation where appropriate. In addition, the software uses the latitude, longitude, and time zone settings set in the Station Configuration dialog.

The Vantage stations' calculated ET_o takes samples of Temperature, Wind Speed, and Solar Radiation over a one hour period and derives an average value. Each time the temperature is sampled, the value of the saturation vapor pressure and actual water vapor pressure are calculated from the current values of temperature and humidity and sampled. These vapor pressure values (in kPa) are used to compute the average saturation vapor pressure and the average water vapor pressure for the hour. The Vantage consoles have the capability to perform floating point arithmetic.

GENERAL ET_O CALCULATION

Measured Variables

T_F mean air temperature in tenths of a degree Fahrenheit

U_{MPH} mean wind speed in whole miles per hour
R_s mean solar radiation in whole Watts per square meter
H mean humidity in percent (value is between 0 and 100).
P_{in} atmospheric air pressure (not corrected for elevation) at the end of the hour; thousandths of inches of mercury.

Calculated Values
(unit conversions)

T_C mean temperature in Celsius

$$T_c = (T_F - 32) * 5/9$$

T_K mean temperature in Kelvin

$$T_K = T_C + 273.16$$

P_{kPa} atmospheric pressure in kPa

$$P_{kPa} = P_{in} * 33.864$$

$U_{m/s}$ mean wind speed in meters per second

$$U_{m/s} = U_{MPH} * 0.44704$$

R_n average net radiation over the hour as described in the next section. Watts per square meter

e_a saturation water vapor pressure in kPa

$$\mathrm{e}_a = 0.6108 * e^{\left(\frac{17.27 * T_C}{T_C + 237.3}\right)}$$

e_d actual water vapor present

$$\mathrm{e}_d = \mathrm{e}_a * \frac{H}{100}$$

Δ slope of the saturation vapor curve at T_C

$$\Delta = \frac{\mathrm{e}_a}{T_K} * \left(\frac{6790.4985}{T_K} - 5.02808\right)$$

γ psychometric constant

$$\gamma = 0.000646 * (1 + 0.000946 * T_C) * P_{kPa}$$

W weighting factor that expresses the relative contribution of the radiation component

$$W = \frac{\Delta}{\Delta + \gamma}$$

F the wind function indicates the amount of energy that the wind contributes towards ET. There are two functions, one for day (solar radiation > 0) and one for night.

$$F_d = 0.030 + 0.0576 * U_{m/s}$$

$$F_n = 0.125 + 0.0439 * U_{m/s}$$

λ latent heat of vaporization. Used to convert net radiation in Watts per square meter into the amount of water evaporated in mm

$$\lambda = 694.5 * (1 - 0.000946 * T_C)$$

ET_o the hourly potential ET in mm

$$ET_o = W * \tfrac{R_n}{\lambda} + (1 - W) * (\mathrm{e}_a - \mathrm{e}_d) * F$$

NET RADIATION

Solar radiation is the primary source of energy that drives evapotranspiration, but what is important is the net radiation, incoming radiation minus outgoing radiation, at all wavelengths.

The Davis solar radiation sensor measures incoming radiation in the visible portion of the spectrum. From this we must subtract out the component that is reflected off the plant leaves. This value is called the albedo.

In addition to the radiation in the visible spectrum, we must also take account of the longer wavelength thermal radiation. This is modeled as black-body radiation coming from three sources at the measured air temperature. The first source is the portion of the sky that does not contain clouds, the second source is the portion of the sky containing clouds, and the third source is the ground radiating into the sky. The first two sources are incoming radiation and the third is outgoing radiation. In order to determine the relative contributions of source one and two, we need to calculate the percentage of the sky that is covered by clouds.

The cloud cover fraction is estimated by comparing the actual mean solar radiation received against the amount we would have received if the sky was clear. In order to calculate the clear sky radiation, it is necessary to calculate the height of the sun above the horizon (solar altitude angle). The altitude of the sun depends, in turn, on the latitude, longitude, day of the year, and time of the day.

The net radiation equation cited in the reference section does not represent the exact method that Davis weather stations use to calculate net radiation.

ACCURACY

These equations were modeled after the ones used by the California Irrigation Management Information System (CIMIS), a program run by the California Department of Water Resources. Therefore, the accuracy of the Davis ET_o calculations are made against the ET_o calculations made by CIMIS. Some of the differences between Davis and CIMIS ET_o calculated values are due to differences in resolution, rather than accuracy.

There are two major factors that cause differences between Davis and CIMIS ET_o calculations: differences in sensor measurements, and differences in net radiation values. Davis stations measure wind speed in one mile per hour increments, but maintains a higher resolution for hourly averages.

As explained above, there are several different ways to calculate a hourly average vapor pressure and saturation vapor pressure values. The CIMIS method is to calculate and sample the vapor pressure value as described for the Vantage stations. However, the saturation vapor pressure is calculated from the average temperature. This method will produce a saturation vapor pressure that is equal or lower than the average of the sampled saturation pressures.

The net radiation formula is approximations of the formula CIMIS uses. CIMIS either directly measures net radiation, or uses a formula that includes a provision for an empirically derived cloud cover factor. CIMIS determines this factor either from data collected at the site over a four year period, or from other sites in the same region. Twelve factors are determined, one for each month.

REFERENCES

General reference on ET
Jensen, M .E., Burman, R. D., Allen, R. G., Editors (1990) "*Evapotranspiration and irrigation water requirements.*" ASCE Manuals and Reports on Engineering Practice No 70.

Paper describing CIMIS' equations and methodology:
Snyder, R. L., Pruitt, W. O. (1992). "Evapotranspiration Data Management in California" *Irrigation & Drainage Session Proceedings/Water Forum '92 EE, HY, IR, WR, div/ASCE*

Paper describing net radiation:
Dong, A, Grattan, S. R., Carroll, J. J., Prashar, C. R. K. (1992). "Estimation of net radiation over well-watered grass." *J. of Irrigation and Drainage Engineering*, Vol. 118, No. 3 ASCE

Web sites with useful information
CIMIS home page
http://wwwcimis.water.ca.gov/cimis/welcome.jsp

Provides some guidelines for water requirements for growing landscape plants in California
http://www.owue.water.ca.gov/docs/wucols00.pdf

SUNRISE/SUNSET (Vantage Pro2, Vantage VUE, Vantage Pro, and WeatherLink)

Parameters Used: Latitude, Longitude, Time and Date, Time Zone, Daylight Savings Time Setting

Sunrise and sunset is a matter of finding when, local time, the sun is on the horizon. The following equations describe the position of the sun in the sky:

Solar altitude, α, is the angular distance of the sun above the horizon, given by:

$\sin \alpha = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos h$

φ is latitude, δ is the declination angle of the sun, h is the hour angle

declination angle is the latitude on the earth at which the sun is directly overhead (south latitudes are indicated as a negative number)

hour angle is the non-negative angular distance east or west from directly overhead

These formulas indicate the true geometric position of the sun. When the sun is on the horizon (as in the case of sunrise and sunset), refraction by the atmosphere will alter the apparent position of the sun. Under average conditions, the sun will appear at the horizon when it is actually 34' (0.567°) below the horizon. Since sunrise and sunset is defined as when the upper half of the sun is visible on the horizon, and the radius of the sun when on the horizon is 16' (0.267°), sunrise and sunset are defined when the geometric position of the sun is 50' (0.833°) below the horizon. This is especially critical in polar regions.

The report also generates twilight times. There are three separate twilight times listed for both morning and evening:

Astronomical Twilight (Astro) is defined as the time at which the center of the sun is 18° below the horizon. At this time, stars and planets of sixth magnitude are visible directly above and generally there is no trace of twilight glow on the horizon. It’s the time of complete darkness without an artificial light source.

Nautical Twilight (Naut) is defined as the time at which the center of the sun is 12° below the horizon. Distinguishing the outlines of objects on the ground is impossible past this point toward darkness, thus it marks the point at which navigation is impossible without an artificial light source.

Civil Twilight (Civil) is defined as the time at which the center of the sun is 6° below the horizon. At this time, stars and planets of first magnitude are visible and suspension of outdoor activities is required (on a clear day) without artificial lighting. Civil twilight is roughly 30 minutes long during the equinox.

The procedure to calculate any of these parameters is as follows. Details on the equations used and time convention and unit conversions follow this brief description:

1. First assume that a sunrise event occurred at 6:00 am local time, a sunset event at 6:00 pm local time. The equations used to describe the position of the sun already require a time, so we must make a first "guess" as to when the event will be.
2. Convert this local time to UTC time. The equations used to define the position of the sun (in this case, on the horizon) use UTC time.
3. Calculate the **declination** and subsequently the **hour angle** of the sun using this UTC time and the specified solar altitude of the given event.

4. Convert the resultant **hour angle** (which is in geometric coordinates) to UTC time.
5. Take the resultant UTC time to again *recalculate* the **declination** and subsequently the **hour angle** using this more accurate indication of the position of the sun.
6. Convert the resultant **hour angle** (which is in geometric coordinates) to UTC time.

To calculate the **hour angle** of the sun, *h*, at the given altitude (which is defined by sunrise/sunset or the twilight parameters), so rearranging the equation for the sun's altitude above for the hour angle, we get:

$$\cos h = \frac{\sin \alpha - \sin \phi \ \sin \delta}{\cos \phi \cos \delta}$$

If the result of this equation is undefined, that is, cos $h > 1$ or $h < 1$, then the event did not occur.

Otherwise, we can solve for $\cos^{-1}(h)$. The value of *h* here is an angle, which must be converted to a 24 hour time base. The procedure is as follows:
Convention: h = 0 = midnight, *h* = 90 = 6:00 am, *h* = 180 = noon, *h* = 270 = 6:00 pm
If h is determined to be a sunrise, then $(180 - h)/15$ is the value in hours (and fractions of hours), otherwise
If *h* is determined to be a sunset, then $(180 + h)/15$ is the value in hours (and fractions of hours)
The result is in **solar time**, which, in this convention, at Noon, the **mean sun** is at its highest point in the sky for the day, which can differ considerably from local time.

The sun's **declination** angle, δ, is determined as follows:

$\delta = \sin^{-1} (\sin T \sin \varepsilon)$

$T = L + C$

$L = (280.46646 + 0.98564736*days)$

$C = ((1.914602-0.00000013188*days)*\sin M +$
$(0.019993-0.000000002765*\text{days})*\sin 2M)$

$\varepsilon = 23.43929°$

$M = (357.52911 + 0.985600281*days)$

where *days* (including fractional days) is the number of days since Jan 1st, 2000, 12:00 UTC in UTC

T is the true anomaly of the sun (the angular distance between where the earth is closest to the sun is its orbit and the actual position in orbit)

L is the mean longitude of the sun (mean angular distance measured around the earth's orbit from the position at the time of equinox)

C is the center of the sun or the difference between the true, *T*, and mean, *M*, anomalies of the sun (determines the location of the sun resolving the differences between the actual position of the sun and the position the sun would have if the earth's angular motion were uniform)

M is the mean anomaly of the sun (same as true anomaly except it assumes the earth moves around the sun at a constant angular velocity), same as mean anomaly of the earth

ε is the obliquity of the earth (the amount the earth is tilted on its axis), which is constant for a century or so (It has an error in the year 2100 of only 0.013° when this constant is used.)

Note: these equations assume that the sun revolves around the earth, for simplicity. However, when addressing the positions in orbit, it is actually the earth revolving around the sun, so this should be understood when trying to understand the physical meaning described in the definitions.

Time Conversions

First, convert local mean solar time to local actual solar time. (Note: When calculating sunrise and sunset, the 6:00 am or 6:00 pm local time is considered actual solar time for simplicity. In the second iteration, when higher precision is needed, the result, local mean solar time, is corrected to actual solar time):

Actual Solar Time = Local Mean Solar Time – E

$E = y \sin 2L - 2e \sin M + 4ey \sin M \cos 2L$

where e is eccentricity of the earth's orbit (how much of an elliptical shape it has) as described below, and M is the sun's mean anomaly and L is the sun's mean longitude as described earlier

$e = 0.016708634 - 0.0000000011509 * days$

$y = \tan^2 (\varepsilon / 2)$

where ε is obliquity as described earlier

The equation of time must be taken into account in order to determine the exact local time (as opposed to the local mean time). This specifies the difference between apparent time and mean time. Stated another way, it is the difference between the true position of the sun and the mean position of the sun. The mean sun assumes that its motion across the sky is uniform.

Then to convert to actual local solar time to local civil time (local civil time is refers to the time convention used by the public at large within a given time zone), take into account how far west or east of the "standard meridian" for their particular time zone. Fractions of minutes must be incorporated to avoid rounding errors. The **standard meridian** is determined as follows:

Standard Meridian = |(UTC Offset)| * 15

UTC Offset should include whether or not Daylight Savings Time is currently in use and be the absolute value or always positive value of the offset in this case.
Then, determine the offset from the standard meridian in hours:

Local Offset = (Standard Meridian - Longitude) / 15

Summarized, the formula for determining sunrise and sunset in local civil time:

Local Civil Time = Mean Solar Time – E + Local Offset

The Davis software further converts the results into UTC so a standard time base is used and thus, it is much easier to use any combination of Time Zone and latitude/longitude coordinates. Some may prefer to have the sunrise/sunset times in UTC. Others, for example, may want to determine what time it is in San Francisco when the sunrise in Tokyo occurs. Here is the relationship between UTC and local civil time:

UTC = Local Civil Time − UTC Offset

In general, UTC offsets are negative if the longitude is west, positive if east. The UTC Offset includes any corrections for Daylight Savings Time (if specified) and must be converted into hours and minutes as needed.

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"Smithsonian Meteorological Tables". Smithsonian Institution Press, Washington, DC, 4th Ed. 1968.

WET BULB

What is it:

Wet Bulb is the temperature to which air must be cooled through evaporation to achieve saturation (100% relative humidity). Wet Bulb can be used to predict when rain changes to snow, how effective warm weather cooling methods can be (especially alternative cooling methods, such as evaporative coolers, a.k.a., "swamp coolers" and cooling towers), and whether farmers can use irrigation methods to mitigate frost and freezing of crops. Like dew point, which is the temperature air must be cooled through radiative cooling to achieve saturation, it can also be used an indicator of the moisture content of the atmosphere. Higher readings indicate higher moisture content, lower readings indicate lower moisture content.

Historically, meteorologists have measured this variable directly using a sling-psychrometer. This instrument consists of two thermometers, with one that has a cotton sock on its bulb. This sock is soaked in water and then manually slung around, or, in automated versions, a fan turns on to dry out the wick. As the water on the sock dries or "wicks", it cools through evaporation. When the temperature stops dropping, this is called the wet bulb temperature. Using a psychometric chart, this reading can be translated into relative humidity or dew point readings using this wet bulb temperature and the air temperature, or "dry" bulb temperature. When the relative humidity is 100%, no evaporation can occur, and the wet and dry bulbs will read the same value, so the web bulb temperature is equal to the air temperature.

The following method is used by Davis Instruments to calculate wet bulb. It uses the principle of Normand's Rule and is the mathematical equivalent of what meteorologists would use to graphically solve for the value using a Skew-T Log, which is a thermodynamic chart of the atmosphere.

$Tw = TLCL + \Gamma s*LCL$,

Where LCL is the Lifting Condensation Level, or the elevation that a parcel of air would have to be lifted to so that is it saturated, or, condensation may start to occur. At this elevation, the relative humidity would be 100% and the air temperature and dewpoint would be equal. This elevation is described by the simple equation $LCL = a*(T – Td)$, where T is the air temperature and Td is the Dew Point Temperature and a is a constant of 0.125. Temperature here can either be expressed in degrees C or Kelvin because it is a difference.

TLCL is the temperature at this Lifting Condensation Level height, which can be found as $TLCL = T – \Gamma d*LCL$, where Γd is the dry adiabatic lapse rate, or the temperature decrease (increase) a parcel of air would experience rising (or falling) through the atmosphere, which is a constant 9.8°C/km. The term is expressed here in the negative because the air is rising in this case.

Γs is the moist adiabatic lapse rate, or the temperature change of a parcel of air after saturation occurs. It is more complex to calculate, can be found knowing other humidity variables in the Davis Instruments equation library and the absolute pressure (which is necessary or the elevation as a reasonable approximation):

$Numerator = 1 + ((rs*Lv)/(Rd*T_K))$

$Denominator = Cp + ((Lv^2*rs*\varepsilon)/(Rd*T_K^2))$

$\Gamma s = g * 1000 * (Numerator/Denominator)$

The secondary equations and constants are defined as the following:

$rs = ((\varepsilon * es)/(P - es))$, the saturated mixing ratio of saturated air to dry air

Lv is the latent heat of vaporization, a constant: 2,501,000 J/kg

Rd is the dry air gas constant: 287 J/kg K

T_K is the air temperature, and must be expressed in degree Kelvin in this case

$Cp = Cpd*(1+0.84*r)$, specific heat of the actual air

$\varepsilon = 2.87/4.615$, the ratio of the gas constants of dry air and saturated air

g is the acceleration due to gravity, assumed to be a constant 9.8 m/s^2

Equations and constants that support the Cp equation:

$es = 6.112 * \exp[(17.62*T_C)/(T_C + 243.12)]$ (also used in our dewpoint calculation)

Cpd is the specific heat of dry air, a constant of 1005.7 J/kg K

$r = ((\varepsilon * e)/(P - e))$ where P is the absolute pressure (which is either calculated or measured from the barometer or approximated from the elevation).

$e = es * RH * 0.01$, where RH is the Relative Humidity in %.

The following describes the method to calculate the approximate absolute pressure from the elevation:

$S = S_{SLP} *0.01 * Bracket \wedge Exponent$

S_{SLP} is 101325 Pascals (not mb)

$Bracket = T_{KSL} /(T_{KSL} + \Gamma * z)$

T_{KSL} is the temperature of the Standard Atmosphere at sea level, 288.15 Kelvins., Γ is the lapse rate of the Standard Atmosphere: -0.0065 K/meter or °C/meter, and z is the elevation.

$Exponent = (g * M / R * \Gamma)$

g is the acceleration due to gravity, assumed to be a constant 9.80065 m/s^2, M is the molar mass of earth's air, 0.028964 kg/mol, R is the universal gas constant for the atmosphere, 8.31432 in J/(mol K)

REFERENCES

Meteorology Today for Scientists and Engineers, Second Edition, Roland B. Stull