

DERIVED VARIABLES IN DAVIS WEATHER PRODUCTS

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 Pro[®] and Vantage Pro2[™] 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 new formula 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 old formula did.

Formulas:

Older versions of software (Versions 5.0 and earlier) and firmware (Vantage firmware revisions before Sept. 7, 2001 and all non-VantagePro products including Echo) are based on the following formula (Siple and Passel, 1945):

$$0.0817 * (3.71 V^{0.5} + 5.81 - 0.25 V) * (T - 91.4) + 91.4$$

where V is the wind speed in mph and T is the outside air temperature in °F. Wind speeds above 55 mph are set to 55 mph. For wind speeds below 5 mph or temperatures above 91.4°F, the wind chill is set equal to the air temperature.

Newer product revisions (WeatherLink version 5.1 through 5.5.1 and Vantage Pro and Vantage Pro2 consoles with Sept 7, 2001 firmware or later and Vantage Pro2 consoles with firmware before May 2005) are based on the following formula:

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

As with the old formula, any place where the result yields a wind chill temperature greater than the air temperature, the wind chill is set equal to the air temperature. This always occurs at wind speeds of 0 mph or temperatures above 76°F. This also occurs at lower wind speeds with temperatures between 0°F and 76°F.

The new formula 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.

An even newer version of this formula is available in WeatherLink version 5.6 or later and Vantage Pro2 console firmware version and later. 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. The later version

for the console table only differs in that whole degrees and less resolution in the table are used for code and memory space conservation. As with previous versions of the wind chill formula, any place where the result yields a wind chill temperature greater than the air temperature, the wind chill is set equal to the air temperature. This always occurs at wind speeds of 0 mph or temperatures at or above 93.2°F (34°C). This also occurs at lower wind speeds with temperatures between 0°F (-18°C) and 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 Pro and Vantage Pro2 console uses 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). All other products use the current wind speed to determine wind chill.

The reason an average wind speed is employed in the Vantage Pro and Vantage Pro2 to calculate wind chill is as follows: The human body has a high heat capacity, thus high wind speeds 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:

Older versions of software and the display console using the following methodology. This formula is based upon the lookup table presented by Steadman (1979). The Davis implementation simply extends the range of use of this table to make it usable at temperatures beyond the scope of the table. Some of this extension is based on the table adapted by the US National Weather Service. The GroWeather and EnviroMonitor systems do not display a value beyond the scope of the Steadman table. All other products that display this value either:

- Set values at temperatures below the scope of the table to the air temperature
- Extend the readings using a best-curve fit above and below the air temperature scope of the table. The low temperature cutoff is when the heat index for the given combination of temperature and humidity is 14°C or 57.2°F or below. This corresponds to a vapor pressure of 16 hPa. Heat Indices are set equal to the air temperature or 57.2°F, whichever is less, below these values. (The 14°C cutoff corresponds to the equivalent dewpoint at average testing laboratory conditions.)

WeatherLink software versions 5.2 or later and Vantage Pro2 console firmware versions of May 2005 revision or later use the above methodology with the following exceptions for values below an air temperature of 68°F:

- The values use a variable baseline to which the Heat Index is either above or below the air temperature.
- The values are loosely derived from the methodology outlined by Steadman in his 1998 paper (referenced below). 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 and as such is displayed in WeatherLink version 5.6.

The latest version for the console table only differs in that whole degrees and less resolution in the table are used for code and memory space conservation.

Note: Heat Index has also been referred to as "Temperature-Humidity Index" and "Thermal Index" in some Davis products.

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 $\geq 50\%$, 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:

$$v = RH * 0.01 * 6.112 * \exp \left[\frac{(17.62 * T)}{(T + 243.12)} \right],$$

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, T_d , can be found:

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

$$\text{Denominator} = 19.43 - \ln v$$

$$T_d = \text{Numerator} / \text{Denominator}$$

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.

The Vantage Pro and Vantage Pro2 console uses a lookup table and it only differs from the formula in that whole degrees and less resolution in the table are used for code and memory space conservation.

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. Thus, this index indicates the level of thermal comfort including the effects of all these values.

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.

The Vantage Pro and Vantage Pro2 calculation is an improvement over the THSW Index in the Health EnviroMonitor because the Health system:

- only calculates THSW Index when air temperature is at or above 68°F.
- assumes the sky is clear.
- assumes the elevation is sea level.

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.

Note: Heat Index has also been referred to as "Temperature-Humidity Index" and "Thermal Index" in some Davis products

WIND FACTOR

The second term is wind. Depending upon your version of firmware or software, this term is determined in part by a lookup table (for temperatures above 50°F) and in part by the wind chill calculation, or uses an integrated table that is used both for calculation of this term and for wind chill. With this in mind, the following criterion apply with later versions referring to Vantage Pro2 console firmware revision May 2005 or later or WeatherLink version 5.6 or later:

- At 0 mph, this term is equal to zero.
- For temperatures at or above 68°F and wind speeds above 40 mph, the wind speed is set to 40 mph. For later versions, there is no upper limit on wind speed.
- For temperatures at or above 130°F, this term is set equal to zero. For later versions of this algorithm: WeatherLink uses 144°F as the threshold; Vantage Pro2 console firmware 143°F. This is based on a best-fit regression of the Steadman 1979 wind table. The differences are reflective of the higher resolution used in the WeatherLink software.

- For temperatures below 50°F (later versions use the new wind chill formula result here (calculate the wind chill increment using the difference between the air temperature and wind chill)):
 - For the earlier display console versions and WeatherLink version 5.0 or 5.1: use the wind chill calculation as the base temperature.
 - For the WeatherLink software (versions 5.2 through 5.5.1): use the new heat index formula (as described in the heat index section) as the base temperature and calculate the wind chill increment using the difference between the air temperature and wind chill (which is always a negative number).

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 (version 5.2 through 5.5.1) offers a variable does not include the sun term in its calculation. It shows the result as 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, Q_g , 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 in the Vantage Pro2 console firmware and WeatherLink software versions 5.6 or later.

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 Pro and Vantage Pro2 measures atmospheric pressure. When entering the location's altitude in Setup Mode, the Vantage Pro and Vantage Pro2 calculates 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 Pro and Vantage Pro2 systems only:

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

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

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 (provided in the attached 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, T_v can be determined. From this, the following can be computed:

$$\text{Exponent} = [Z/(122.8943111 * T_v)]$$

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

$$R = 10^{[\text{Exponent}]}$$

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. Subsequently, output data using the VantageLink 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 Pro and Vantage Pro2 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 unit is functioning properly, is:

- use a reference that has been adjusted to indicate sea-level pressure and setting the Vantage Pro and Vantage Pro2 console to the proper elevation or
- use a reference that is reading the raw, uncorrected atmospheric pressure and set the Vantage Pro and Vantage Pro2 console elevation to zero

and verify that these readings are comparable.

ALTIMETER SETTING and CWOP APRS

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 "2 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:

$A = (P^N + K \cdot Z)^{1/N}$, 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

Unlike previous Davis systems, the Vantage Pro and Vantage Pro2 comes with only one type of rain collector. It is equipped with a 0.01" rain collector. All Vantage Pro and Vantage Pro2s physically measure in increments of 0.01 in. The system has a provision for other types should they be added in the future.

The Vantage Pro and Vantage Pro2 is pre-configured for this type of rain collector. In the series of "Setup Screens", there is one for "Rain Collector". Simply press the DONE key to move to the next screen. By default, it should be set to ".01" Rain Collector". If it isn't, use the "+" and "-" arrow keys to select this type.

The rain display's units may be changed from inches to millimeters by pressing 2ND, then the UNITS key while in "Current Screen" mode with one of the rain fields selected. If millimeters is displayed, the console converts from inches to mm. If display millimeters is displayed, the counter will occasionally skip a reading due to rounding.

RAINFALL RATE

Parameters Used: Rain Total (actually, 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 rain storm 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 Pro, Vantage Pro2, and WeatherLink 5.X+ only)

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:

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

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):

- $D = 20:57$
- $6.289^\circ \sin M' = 8:35$
- $2.1^\circ \sin M = 4:26$
- $1.274^\circ \sin (2D - M') = 1:56$
- $0.658^\circ \sin 2D = 0:38$

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:

$$D = 297.8501921 + 12.19074911 * \text{days}$$
$$M' = 134.9633964 + 13.06499295 * \text{days}$$
$$M = 357.52911 + 0.985600281 * \text{days},$$

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 $i \geq 180^\circ$, 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

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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_0). ET_0 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_0 for a grass reference.

To determine actual ET from a reference ET_0 , multiply the ET_0 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_0 .

THE DIFFERENT DAVIS ET_0 CALCULATIONS

There are three ways that ET is calculated by Davis weather stations. They differ in how the weather data values are gathered and in how Net Radiation is calculated. The three methods are: GroWeather calculated on the console, GroWeather calculated on a PC, and Vantage Pro and Vantage Pro2 (calculated on the console). In all methods, hourly ET values are calculated from hourly averages of weather variables. The differences arise from differences in the computational abilities of the GroWeather station, Vantage Pro and Vantage Pro2 station and a PC.

DATA SAMPLING AND VARIABLES REQUIRED FOR CALCULATION

The GroWeather console calculated ET_0 samples Temperature, Humidity, Wind Speed, Solar Radiation over a one hour period. This sampling is independent of sampling undertaken for the creation of archived data records. At the end of the hour, the arithmetic mean is calculated for each value by dividing the sum of the sampled data values by the number of samples taken. The number of samples is tracked for each sensor independently in case some sensors are not connected for some part of the period. In addition, the raw Barometer value (i.e. not corrected for altitude) at the end of the hour is read.

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.

The GroWeather PC calculated ET_o uses data from the historical archived data to calculate the average temperature, humidity, wind speed, solar radiation; and the final atmospheric pressure. In addition, the software uses the latitude, longitude, and time zone settings set in the Station Configuration dialog.

The Vantage calculated ET_o takes samples of Temperature, Wind Speed, and Solar Radiation over a one hour period and derives an average value in a manner similar to the GroWeather console. Instead of sampling the humidity and deriving an “average humidity” for the hour, 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 has the capability to perform floating point arithmetic.

GENERAL ET_o CALCULATION

For the most part, these equations are applicable to all 3 calculation methods. Where they differ they are marked as follows: (GWc) applies to the GroWeather Console calculation, (GWpc) applies to the GroWeather PC calculation, and (VP) applies to the Vantage 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). (GWc and GWpc only)
 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

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

e_d actual water vapor present

$$e_d = e_a * \frac{H}{100}$$

Δ slope of the saturation vapor curve at T_C

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

γ psychrometric 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

$$ET_o = W * \frac{R_n}{\lambda} + (1 - W) * (e_a - e_d) * F$$

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.

On the GroWeather, all wind averages are in one mile per hour increments, whereas CIMIS data has a higher resolution. The Vantage Pro and Vantage Pro2 measures 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 Pro and Vantage Pro2. 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 given above are all 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://wwwdpla.water.ca.gov/cgi-bin/cimis/cimis/hq/main.pl>

Provides some guidelines for water requirements for growing landscape plants in California

<http://wwwdpla.water.ca.gov/urban/conservation/landscape/wucols/index.html>

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

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:

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

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:

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

$$T = L + C$$

$$L = (280.46646 + 0.98564736 * \text{days})$$

$$C = ((1.914602 - 0.00000013188 * \text{days}) * \sin M + (0.019993 - 0.00000002765 * \text{days}) * \sin 2M)$$

$$\epsilon = 23.43929^\circ$$

$$M = (357.52911 + 0.985600281 * \text{days})$$

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

$$e = 0.016708634 - 0.0000000011509 * \text{days}$$

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

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:

$$\text{Standard Meridian} = |(\text{UTC Offset})| * 15$$

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:

$$\text{Local Offset} = (\text{Standard Meridian} - \text{Longitude}) / 15$$

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

$$\text{Local Civil Time} = \text{Mean Solar Time} - E + \text{Local Offset}$$

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:

$$\text{UTC} = \text{Local Civil Time} - \text{UTC Offset}$$

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

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