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Measurement and Reporting Practices for Automatic Agricultural Weather Stations

American Society of
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STANDARD

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Measurement and Reporting Practices for Automatic Agricultural Weather Stations

Developed by the ASAE SW-244 Irrigation Management Subcommittee; approved by the ASAE Soil and Water Division Standards Committee April 2004.

1 Purpose and scope

1.1 Purpose: The purpose of this Engineering Practice is to establish minimum recommendations for measurement, reporting, siting, operation, maintenance, and data management procedures for automatic agricultural weather stations. Additionally, these recommended procedures are intended to assist in the planning of automatic agricultural weather station installation and operation.

1.2 Scope: This Engineering Practice applies to automatic weather stations installed individually, or as part of a network of stations, for the measurement and reporting of specific weather variables in agricultural environments. This Engineering Practice also addresses a recommended core set of measurements and general siting considerations for agricultural weather stations. It is recognized that special purpose agricultural weather stations may deviate from the recommendations herein, particularly with respect to sensor deployment and station siting conditions. This Engineering Practice does not specifically address these special purpose stations.

2 Normative references

The following standard contains provisions that, through reference in this text, constitute provisions of this Engineering Practice. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Engineering Practice are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Standards organizations maintain registers of currently valid standards.
ASAE S526.2 JAN01, *Soil and Water Terminology*.

3 Definitions

3.1 Definitions. For the purpose of this Engineering Practice only, the following definitions are defined herein. Additional terminology is defined in ASAE Standard S526, Soil and Water Terminology.

3.2 adiabatic lapse rate. The decrease in temperature of a parcel of air with height above the surface when lifted in elevation adiabatically, that is, without the addition or withdrawal of heat from the surrounding air. The adiabatic lapse rate of dry air is about 1°C/100 m.

3.3 anemometer: Instrument for measuring the speed of the wind.

3.4 atmospheric (barometric) pressure: The pressure exerted by the weight of air (dry air and water vapor mixture) above a given point.

3.5 automatic agricultural weather station: A stand-alone set of equipment designed to automatically measure and record agriculturally significant weather variables, as specified in clause 4, for agricultural purposes. The station is based on an electronic data logger and includes associated sensing devices, power supplies, environmental enclosures, and support structures, normally operated on a year-round basis at a fixed location and it may be part of a network of similar stations. It collects data at a specified sampling interval(s), stores intermediate measurements in memory, processes summary values at a specified reporting interval, and stores the summary values in memory. Finally, it incorporates some means of data telemetry for access to, or transfer of, summary values, typically on a near-real time basis, to a central location for more general processing, long-term storage and dissemination, or to alternative on-site exchangeable storage media.

3.6 climate day: A 24-hour period (e.g., midnight to midnight, 8 am to 8 am, local standard time) for which a statistical summary of the measured weather values is prepared (means, maximums, minimums, totals, etc.)

3.7 data logger: An electronic, microprocessor-based device that can be programmed to make measurements of specific sensors, to process the measurements, and to store intermediate measurements and summary data values.

3.8 dew-point temperature: The temperature to which moist air at a specific barometric pressure, relative humidity, and temperature must be cooled to reach moisture saturation.

3.9 dry-bulb temperature: Ambient air temperature.

3.10 evaporation: The process by which a liquid changes into a gas.

3.11 fetch: The extent of homogeneous area surrounding a given point.

3.12 fully adjusted layer: Approximately the lowest 10% of the internal boundary layer that is in complete equilibrium with new surface boundary conditions caused by a transition in surface conditions.

3.13 internal boundary layer: The layer of air downwind of a transition in surface characteristics such as surface roughness; its thickness increases with distance downwind, or down fetch.

3.14 psychrometer: Instrument used to measure the water vapor content of the air by measuring the wet-bulb and dry-bulb temperature of the air.

3.15 radiation shield: A device used for housing air temperature sensors that reduces the temperature effects of radiation on the sensor.

3.16 resistance temperature detector: A length of pure metal (wire), carefully wound in a stress free form, that increases in resistance as the temperature of the metal (wire) increases.

3.17 sampling interval: The time interval between successive measurements of a sensor, or sensors, by a data logger.

3.18 saturation vapor pressure: The partial pressure exerted by water vapor when it is in equilibrium with a plane surface of pure water.

3.19 sensor: A device that provides a measurable signal output in response to a physical stimulus or variable.

3.20 soil heat flux: The flow of heat energy per unit cross-sectional area into, or out of, the soil.

3.21 solar radiation (irradiance) (direct, diffuse, global, longwave, net, shortwave): Direct solar radiation is the radiation coming from the solid angle of the sun's disc; irradiance is the property that is measured. Diffuse, or sky radiation, is downward, scattered and reflected solar radiation coming from the whole hemisphere. Global radiation is the sum of direct and diffuse solar radiation. Longwave radiation is the infrared energy emitted by the earth and the atmosphere. Net radiation is the sum of net shortwave radiation and net longwave radiation. Shortwave radiation is the radiant energy emitted from the sun at wavelengths less than 4 microns.

3.22 surface roughness: Aerodynamic roughness of a surface; a parameter affecting the downward transport of horizontal momentum from airflow to a surface.

3.23 telemetry: The transmission of data collected at a remote location to a central station, using one or more means of communication.

3.24 thermal stability: A concept describing the variation of temperature with elevation in the atmosphere. When the actual air temperature decreases with height above the surface at a rate greater than the dry adiabatic lapse rate (about 1° C/100 m), the atmosphere is unstable, the temperature is termed a lapse profile, air is buoyant, and turbulence or mixing is enhanced. When the actual air temperature decreases with height above the surface at a rate less than the dry adiabatic lapse rate, the atmosphere is stable, the temperature profile is termed an inversion, air tends to hold its position vertically, and turbulence or mixing is suppressed. When the actual air temperature profile equals the dry adiabatic lapse rate, the atmosphere is neutral.

3.25 thermistor: An electrical resistance device for measuring temperature that exhibits rapid and large changes in resistance for relatively small changes in temperature.

3.26 thermocouple: A device consisting of two dissimilar metals joined together at their end that produces a thermoelectric voltage proportional to the temperature difference between the two junctions.

3.27 time constant: The time required for an instrument to make a 63.2 percent adjustment to new environmental conditions, in which the measurement system is a linear, first-order, time-invariant, step function input. This percentage is equal to the quantity (1-1/e) where e is the base of the natural logarithm, 2.7182.

3.28 vapor pressure (actual): The pressure exerted by the water vapor molecules in air at a given temperature.

3.29 wet-bulb temperature: The temperature to which moist air can be cooled adiabatically (without any gain or loss of heat) by evaporation.

3.30 wind speed: Horizontal movement of air in distance per unit time.

3.31 wind direction: The direction from which air is moving.

3.32 wind vane: Instrument used to indicate wind direction.

3.33 zero plane displacement: The mean level, or height, at which momentum is absorbed by individual elements on a surface, e.g., plant leaves.

4 Measurements

4.1 Variables

4.1.1 Core variables. The recommended core variable set to be measured on an agricultural weather station should include solar radiation, air temperature, relative humidity, wind speed, wind direction, rainfall (total and intensity), and soil temperature (Table 1).

4.1.2 Derived variables. Variables derived from the core set of measured variables and applicable formulae for their derivation should include (see Table 1):

4.1.2.1 Saturation vapor pressure. Saturation vapor pressure should be calculated and logged with each sampling of air temperature and may be determined using an equation such as that of Tetens (1930) or Murray (1967):

$$e^o = \exp[(16.78T - 117)/(T+237.3)]$$

Allen et al. (1994) give the Tetens (1930) equation as:

$$e^o = 0.611\ \mathrm{EXP}\ [17.27\ T/(T+237.3)]$$

and Allen et al. (1998) give the Tetens (1930) equation as:

$$e^o = 0.6108\ \mathrm{EXP}\ [17.27\ T/(T+237.3)]$$

where:

e^o = saturation vapor pressure (kPa)

T = air temperature (°C)

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Lowe (1977) gives an equation for saturation vapor pressure as,

$$e^o = a_0+T(a_1+T(a_2+T(a_3+T(a_4+T(a_5+a_6T)))))$$

where:

e^o = saturation vapor pressure (kPa)
T = air temperature (K)
a_0 = 698.450 529 4
a_1 = −18.890 393 10
a_2 = 0.213.335 767 5
a_3 = $-1.288\ 580\ 973\times10^{-3}$
a_4 = $4.393\ 587\ 233\times10^{-6}$
a_5 = $-8.023\ 923\ 082\times10^{-9}$
a_6 = $6.136\ 820\ 929\times10^{-12}$.

Note that a different formula for saturation vapor pressure with respect to an ice surface should be used. The definition of relative humidity requires the use of saturation vapor pressure with respect to a water surface at all temperatures.

4.1.2.2 Actual vapor pressure. Actual vapor pressure of the air should be calculated and logged with each sampling of air temperature and relative humidity, and is determined by:

$$e_a = e^o\ (RH/100)$$

where:

e_a = actual air vapor pressure (kPa)

RH = relative humidity (%).

4.1.2.3 Vapor pressure deficit. Vapor pressure deficit should be calculated and logged with each sampling of air temperature and relative humidity, and computed using:

$$VPD = e^o - e_a$$

where:

VPD = vapor pressure deficit (kPa).

4.1.2.4 Wind data reduction. Scalar mean wind speed, unit vector mean wind direction, resultant mean wind speed and direction, and standard deviation of wind direction may be computed using raw sampled data values in the following relationships:

$$W = \Sigma(w_i)/n$$

$$\theta_u = \tan^{-1}\ (w_x/w_y)$$

$$w_x = \Sigma(w_i \sin\theta_i)/n$$

$$w_y = \Sigma(w_i \cos\theta_i)/n$$

$$U = (w_x+w_y)^{0.5}$$

$$\theta_1 = \tan^{-1}(w_{x1}/w_{y1})$$

$$w_{x1} = \Sigma(\sin\theta_i)/n$$

$$w_{y1} = \Sigma(\cos\theta_i)/n$$

$$\sigma(\theta_u) = 81(1-U/W)^{0.5}$$

$$\sigma(\theta_1) = \sin^{-1}(\varepsilon)[1+0.1547\varepsilon^3]$$

$$\varepsilon = [1-(w_{x1}{}^2+w_{y1}{}^2)]^{0.5}$$

where:
W = scalar mean horizontal wind speed (ms^{-1})
w_i = sampled wind speed data values (ms^{-1})
n = number of samples
θ_u = resultant mean wind vector direction (degrees)

w_x = speed weighted mean wind vector component in East-West direction
w_y = speed weighted mean wind vector component in North-South direction
θ_i = sampled wind direction data values (degrees)
U = resultant mean wind vector magnitude (ms^{-1})
θ_1 = unit vector mean wind direction (degrees)
w_{x1} = mean unit vector component in East-West direction
w_{y1} = mean unit vector component in North-South direction
$\sigma(\theta_u)$ = standard deviation of wind direction, Campbell Scientific algorithm (CSI, 1987)
$\sigma(\theta_1)$ = standard deviation of wind direction, Yamartino algorithm (US EPA, 1987).
x,y = coordinate system in the horizontal plane with x-axis aligned with East.

4.1.3 Supplemental variables. Supplemental and additional variables which may be measured or derived on an automatic agricultural weather station include: net radiation; photosynthetically active radiation; air temperature, relative humidity, and wind speed at heights other than those specified in Table 1; soil temperature at depths other than those specified in Table 1; soil temperatures under other surface conditions; standard deviation of wind speed (see clause 4.1.2.4); dew-point temperature; soil water content; soil heat flux; leaf wetness; barometric pressure; surface temperature; evaporation (by Class A Pan or atmometry if successfully automated, otherwise evapotranspiration is calculated); solid precipitation (snow fall and snow depth). Suitable algorithms exist for the estimation of some of these variables using the measured standard variable set, e.g., net radiation, soil heat flux, evapotranspiration, photosynthetically active radiation.

4.2 Units. All measured and derived variables should be reported in SI (metric) units. See Table 1 for recommended units for each variable.

4.3 Deployment. Recommended deployment heights and depths for each standard measurement given in clause 4.1 are listed in Table 1. For purposes of reference evapotranspiration computation using a Penman model, daily average wind speed at 2-m height above the surface is required. Daily average wind speed at 2 m may be estimated from the measured data at height z using the following general relationship (Jensen et al., 1990):

$$W_2 = W_z(2/z)^{0.2}$$

where:
W_2 = estimated wind speed at 2-m height (ms^{-1}),
W_z = wind speed (ms^{-1}) measured at height z (m).

Or, to account for measurement surface roughness:

$$W_2 = W_z[\ln((2-d)/z_o)/\ln((z-d)/z_o)]$$

where W_2 , W_z , and z are as previously given and:
d = zero plane displacement height of the measurement surface (m),
z_o = surface roughness height for momentum transfer (m).

d and z_o may be approximated as:

$$d = 0.7\ h_c$$

$$z_o = 0.1h_c$$

where:

h_c = vegetation height (m).

4.4 Sampling interval. Recommended data logger sampling intervals for each measurement given in clause 4.1 are listed in Table 1. It is probable the data logger will be programmed to sample at the smallest sampling interval and thus all sensors will be sampled at that rate. The World Meteorological Organization (WMO) standard for wind measurements is a 3-s sampling interval. The Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) has issued a standard method for characterizing surface wind that requires a 3-s sampling interval (OFCM, 1992). When characterization of wind is an important component of the automatic agricultural weather station program, it is advisable to follow the OFCM wind standards. The OFCM standard data output includes additional parameters to those listed in Table 1 for wind speed and direction. Note that a more frequent sampling rate will drain batteries more quickly, making battery maintenance a more important factor for battery-powered stations without solar panels.

4.5 Reporting. Reporting interval and values to be reported for each of the core and derived variables are listed in Table 1. The hourly reporting interval of values specified in Table 1 allows data users to generate summaries for different climate days, i.e., midnight to midnight, 0800 to 0800, etc., as desired. A midnight to midnight daily reporting interval is recommended. Data should always be collected and reported in local standard time.

5 Types of equipment

5.1 Data loggers. A microprocessor-based electronic data logger is the necessary basis of an automatic agricultural weather station. This device must be user-programmable to allow, at a minimum, readings of instruments listed in Table 1 at the recommended sampling intervals listed in Table 1. Additionally the data logger must be capable of intermediate processing of data such as computation of the derived variables listed in clause 4.1.2, storage of intermediate values, computation of the statistical summary values listed in Table 1, and storage of summary values. Finally, the data logger must have appropriate communications interfaces for data transfer to storage media or data telemetry equipment.

5.2 Solar radiation (irradiance) sensors. Total or global solar radiation may be measured with pyranometers or total hemispherical radiometers. Pyranometers may be of the thermopile or photocell types. Instruments should have compensation for temperature dependence. The instrument should have sensitivity across the entire spectral range affecting biological activity. The typical short-wave spectrum is 0.3 to 3 microns.

5.3 Temperature sensors. Air and soil temperature may be measured with thermistors, resistance temperature detectors (RTD), or thermocouples. Thermocouples measure the temperature difference between a measuring junction and reference junction; the reference junction will typically be at a data logger or multiplexer wiring panel, requiring a temperature measurement at the panel. Air temperature sensors must be deployed in a minimum of a naturally-ventilated radiation shield. Soil temperature sensors must be environmentally sealed to prevent moisture penetration and to allow for direct burial in the soil.

5.4 Relative humidity sensors. The most common types of relative humidity sensors used on automated agricultural weather stations measure changes in physical, chemical, or electrical properties of a material upon absorption of water vapor by, or adsorption of water vapor to, the material. These may include strain measurements, or measurements of the change in electrical resistance or capacitance. Psychrometers are generally not used on remote stations due to the high power requirements of the aspirating mechanism and the problem of providing a continuous water supply to the wet-bulb temperature device.

5.5 Wind instruments

5.5.1 Wind speed. Wind speed is typically measured on an automatic weather station using a cup or propeller anemometer; horizontal wind speed is typically the only component measured. Devices may be of switch closure type, optical type, or the type that generates an AC signal or a DC signal.

5.5.2 Wind direction. Wind direction is measured with a wind vane. The measurement will be the direction from which the air is moving. Wind vanes should be aligned relative to true north, i.e., 0 degrees is true north, 90 degrees is east, etc.

5.6 Rain gages

5.6.1 Tipping bucket gages. Tipping bucket rain gages operate on a

Table 1 – Core variable set, units, deployment heights, sampling intervals, and values reported for automatic agricultural weather stations

Variable	Derived variables	Units	Deployment height (m)	Sampling interval (s)	Values reported each hour
Solar radiation	---	W m^{-2}	[1]	$\leq$ 10	average
Air temperature [2]	---	°C	1.5 to 3	$\leq$ 60	average instantaneous max/min
	Sat. vapor pressure	kPa	---	[3]	---
Relative humidity [2]	---	%	co-located with air temperature	$\leq$ 60	average instantaneous max/min
	Vapor pressure	kPa	---	[4]	average
	Vapor pressure deficit	kPa	---	[4]	average
Wind speed [5]	---	m s^{-1}	2 to 3	$\leq$ 10	scalar mean maximum during interval and time of occurrence
Wind direction [6]	---	deg	co-located with wind speed	$\leq$ 10	unit vector or resultant mean magnitude and direction standard deviation
Rainfall [7]	---	mm h^{-1}[8]	$\leq$ 10	[8]	total rate or intensity [8]
Soil temperature [9]	---	°C	-0.10 to -0.20[10]	$\leq$ 60	average instantaneous max/min

Notes for Table 1:

1) Deploy to avoid shading by and reflection from nearby objects. Practical considerations for height include ease of maintenance, i.e., routine cleaning and checking instrument level.
2) Supplemental data, which may be reported, are times of occurrence of maximum and minimum values.
3) Saturation vapor pressure is calculated with each sample of air temperature (see text for equation) and may be reported as supplemental data. See clause 4.1.2.1.
4) Vapor pressure and vapor pressure deficit are calculated with each sample of relative humidity and air temperature. Supplemental data that may be reported are times of occurrence of maximum and minimum values. See clauses 4.1.2.2 and 4.1.2.3.
5) See clause 4.1.2.4. WMO and OFCM standard is 3-second sampling rate for wind speed and direction, see clause 4.4. WMO standard height for wind measurements is 10 m.
6) Azimuth direction referenced to true North. See clause 4.1.2.4 for algorithms for calculating hourly mean wind direction (magnitude and direction) and standard deviation of wind direction from sampled values.
7) Liquid precipitation only.
8) Sampling is event driven for tipping bucket rain gages. To obtain the rainfall rate or intensity, record the time of each tip for tipping bucket gages; for weighing gages, record the total weight and time for each 0.254 mm (0.01 in.) of rainfall to obtain both total rainfall and intensity. Hydrologists recommend a minimum sampling interval of 15 min; 1-min sampling intervals are often used.
9) Measure under bare soil surface conditions. Soil moisture at probe depth should be maintained at levels equivalent to the environment being represented (i.e., irrigated vs. dryland sites).
10) Soil temperature deployment is often dependent on the intended use of the data; the values of –0.10 m and –0.20 m are typical depths of installation.

switch closure principle generating electrical pulses with each tip of a small bucket that receives liquid from a funnel. Knowing the depth represented by each tip and counting the number of tips, the depth of rainfall over a specified time interval can be determined. Rainfall intensity can be determined by recording the time of each tip in addition to counting the tips. Unless heated, tipping buckets are limited to measurement of liquid precipitation.

5.6.2 Weighing gages. Weighing gages weigh and record all forms of precipitation as soon as they fall into the gage. Anti-freeze may be used to avoid ice formation in the bucket and oil may be used to retard evaporation. Weighing gages are sensitive to strong winds, which often cause erroneous readings.

5.7 Data storage/telemetry

5.7.1 On-site data storage. On-site data storage requirements are dependent upon the method and frequency of data retrieval. Data loggers should be equipped with adequate memory to store data for a minimum of several days. Transfer of data to on-site memory or to recording devices (solid state memory, cassette tape, etc.) should occur hourly and daily as per the reporting intervals in Table 1. Frequency of exchange of on-site data storage media is dependent on capacity, data utilization requirements, etc.

5.7.2 Telemetry equipment. Data telemetry to a central computing facility may be accomplished via telephone (standard or cellular) and modem connection, land-based radio frequency telemetry, satellite telemetry, meteor burst technology, etc.

5.8 Other equipment

5.8.1 Station power. Most data loggers operate on direct current (DC) power. Power requirements of the data logger for measurement, and processing and storage of data should be minimal, allowing for extended operation before it becomes necessary to replace batteries. AC power at the weather station site may be used for trickle charging the battery with an appropriate voltage transformer and adequate surge protection. Solar panels may also be used to trickle charge batteries with appropriate voltage regulation. Batteries of the sealed gel-cell type may be housed in the same enclosure as the data logger and telemetry equipment. Wet cell batteries should be housed in a separate enclosure to minimize the risk of hydrogen gas buildup and possible explosion within the data logger enclosure, as well as to avoid corrosion of electronic equipment terminals.

5.8.2 Enclosures. All enclosures should be rainproof. Enclosures housing the data logger should be National Electrical Manufacturer's Association (NEMA) type 4 with a gasket type seal on the door. Ports for sensor leads should be sealed with electrician's putty. Desiccant packs should be kept within the data logger enclosure and maintained according to clause 9.3.5.

5.8.3 Structure. Data logger enclosures, battery enclosures, all sensor mounting arms, etc. should be rigidly attached to the weather station structure. The weather station structure may be a tripod, a free-standing tower, or a guyed tower. The weather station structure should be firmly anchored to the ground and should be equipped with an electrical grounding system connected to an earth ground and a lightning rod. All instruments, the entire tower/structure, and all connections leading to the tower should be connected to a common ground. This ensures that there are no ground loops in the system, where voltage differentials between the instruments and data logger or tower can develop. Sensors not directly mounted on the main station structure should be mounted on their own rigid and anchored structure. Provisions should be made to bring the sensor leads to the data logger in buried moisture-and rodent-proof conduit.

6 Measurement requirement and uncertainty

6.1 General. A fundamental objective of this engineering practice is to define requirements and practices necessary to:

- characterize the uncertainty in measurements obtained;
- obtain measurements of sufficient quality to be useful for the intended agricultural applications or products.

Table 2 – Typical measurement range, resolution, and estimated field accuracy of sensors used on automatic agricultural weather stations

Variable	Range	Resolution Variable	Resolution Digital	Specified accuracy	Estimated field accuracy
Solar Radiation	0 to 1500 W m^{-2}	5 W m^{-2}	(33 μV)	typical: ±3% OR[1] max: ±5% OR	same as specified
Air temperature thermistor (resistance)	−30°C to 50°C	0.1 °C	(1 mV V^{-1})[2]	±0.3°C	aspirated: ±0.5°C unaspirated: +0.5 to 2.5°C −0.5 to −1°C
PRT (resistance)	---	---	(100 μV V^{-1})	±0.2°C±0.15%OR[3] ±0.35° C±0.4%OR[4]	---
Thermocouple	---	---	(4 to 6 μV)	±0.75% of $(T_m - T_R)$[5] ±T_R error	---
Soil Temperature	---	---	---	---	±0.5 °C
Relative humidity	10 to 100% RH	1% RH	(10 mV)	±3% to ±5% RH	±5% RH
Wind speed (frequency)	0.5 to 40 m s^{-1}	0.5 m s^{-1}	---	±0.3 m s^{-1} or ±2% OR	---
Wind direction (vane)	0 to 360 deg	5 deg	(14 mV V^{-1})	±3 to 5 deg	10 deg
Rainfall	0 to 200 mm h^{-1}	0.25 mm h^{-1}	---	---	−10% at 100 mm h^{-1}

Notes for Table 2:
1) OR: Of Reading
2) Units of mV V^{-1} in the digital resolution column reflect resolution required per volt of excitation to resistance of sensor.
3) Class A
4) Class B
5) Specified accuracy for thermocouples is in terms of T_m and T_R, the measurement and reference temperatures.

The quality of measurements obtained requires a compromise between the cost of instrumentation and maintenance, and the need for long-term operation. Estimates of the measurement uncertainty one can expect using sensors and practices commonly employed in long-term weather station operation, are given in Table 2. Sensitivity analyses of various agricultural applications (ET estimation, crop modeling, pest and disease prediction) to expected measurement uncertainty are required to determine the usefulness of measured variables for such applications. If the level of uncertainty reduces the usefulness of the measurements, additional or tighter specifications for both sensors and practices must be considered.

Flexibility in the choice of sensors and instrumentation by weather station operators is desirable. The intent of this section is to provide guidance on desirable measurement ranges and measurement resolution. The choice of sensors influences the maintenance and calibration schedules needed to maintain a desired level of measurement quality.

Types of sensors commonly used in agricultural and climatic networks are listed in Table 2. A number of other sensor options exist beyond those shown. Higher quality sensors may exist, but the information in Table 2 is intended to assist in the selection of a sensor type capable of obtaining the desired quality of measurement. The minimum acceptable quality of data is in part determined by the measurement capability for a given sensor type. The quality of measurement may differ greatly between sensors of the same type, but from different manufacturers.

6.2 Measurement range. The desired measurement range for an individual variable should be specified or known. Table 2 provides general guidance, however, certain regions of the world may not require ranges as broad as those given for some variables (e.g., air temperature).

6.3 Measurement resolution. Two columns are listed under measurement resolution in Table 2; variable resolution is that needed for the specific application(s) of the data. To avoid ambiguity, the resolution should be specified for an individual measurement as opposed to the time-averaged, recorded value. Values given in Table 2 are suggested initial values for evaluation.

Digital resolution is the resolution required of the measurement electronics for a particular type of sensor signal, in order to obtain the accompanying specified variable resolution. Values given in Table 2 are for information purposes only.

6.4 Accuracy

6.4.1 Manufacturer's specifications. Values shown in Table 2 in the specified accuracy column refer to manufacturer's specified accuracy. In some cases the values reflect a specific manufacturer, and in others, a typical value from a distribution provided by several manufacturers of the same type of sensors. The accuracies should be regarded as representative of bench top environments rather than achievable field operational accuracies. Values given in Table 2 are given for information purposes only.

6.4.2 Operational field accuracy. Values shown in Table 2 are representative of the uncertainty of measurements made under field conditions. The values are provided as first estimates for determining their usefulness for agricultural applications.

7 Documentation

7.1 General. Each automatic agricultural weather station site installation should have a station history document developed and maintained for the duration of the installation. This station history file must be available to all potential users of data collected at the weather station. Station grounds conditions and maintenance; sensor condition, maintenance, calibration, and replacement; etc.; should all be included in the station history file. The station history file is important documentation needed for such activities as investigation of data anomalies, etc. The station history file should contain physical information about the site and surrounding area, information about the array of sensors deployed at the site (clause 7.2), site and sensor maintenance information, sensor calibration data (clause 7.3), and descriptions of electronic data retrieval and storage (archival) formats (clause 7.4).

7.2 Site documentation. Each weather station site should be identified with a unique identification label. Written documentation describing the weather station installation site should be developed and periodically updated. Constant geographic data such as station elevation above mean sea level, latitude and longitude to the nearest 30 seconds of arc, and land slope and aspect should be included.

7.2.1 Site description. Site characteristics to be described include: ground cover characteristics (type and height), soil type, and irrigated or rainfed conditions under the station and in the immediate vicinity (radius out to 200 m) of the station. Terrain features (hills, trees, bodies of water, buildings, etc.) of the surrounding local area (radius out to 5000 m) should be described by distance, height, and sector. Written descriptions of the immediate vicinity of the site and local surrounding area should be supplemented with photographs taken in a minimum of each of 8 coordinate directions (45° sectors), and preferably 12 coordinate directions (30° sectors), several times per year (at least twice during the growing season; beginning and mid-season). Average surface roughness in each sector should be characterized and recorded using the roughness classifications given in Table 3.

General comments about the agriculture (irrigated or rainfed, crop types, growing seasons, etc.) in the region of the station (radius up to 50 km) should be included. Descriptions should include natural and anthropogenic-based changes to the area surrounding the site as a function of time during the calendar year (e.g., cropping patterns, growth cycles, etc.).

7.2.2 Sensor exposure description. Written documentation describing the array of sensors deployed at a site and their deployment characteristics (height, depth, orientation, etc.) should be developed and maintained. Sensors should be described by name of manufacturer, serial number, or other identification number. Dates of installation, maintenance and/or calibration activity (clause 7.3), and removal or replacement should be recorded. All changes in sensor deployment characteristics should be documented when they occur.

7.3 Calibration and maintenance documentation

7.3.1 Calibration. All calibration activities should be recorded on a standard form showing part or sensor name or other identifier, serial number, date, and a checklist of activities performed. Deviations of sensor performance from calibration sensors should be noted, both before and after the calibration. Completed forms should be maintained in at least a paper filing system, and preferably, also in an electronic database file. All calibration records should provide a trace of the sensor or part history, and should be cross-referenced with station/sensor maintenance record keeping.

7.3.2 Maintenance. All maintenance activities, whether scheduled routine maintenance or unscheduled emergency maintenance, should be recorded on a standard form showing station name or other identifier, date of visit, and a checklist of activities performed. Record notes on these forms detailing "as found" and "as left" conditions. The form should also contain a checklist for ensuring the station and data logger are left in proper operational state upon completion of the maintenance visit. Completed forms should be maintained in at least a paper filing system for each station, and preferably, also in an electronic database file. All station/sensor maintenance records should be cross-referenced with all calibration records.

7.4 Data documentation. All data should have written documentation, electronic or otherwise, developed and maintained describing means for data access and retrieval. Additionally all data sets should be accompanied with documentation describing storage (archival) formats (see clause 10).

8 Station siting

8.1 Exposure. Ideally, agricultural weather stations should be sited in level, open terrain representative of the local agricultural environment.

Table 3 – Average surface roughness classification (after Wieringa, 1992)

No.	z_0 (m)	Landscape description
1	0.0002 "Sea"	Open sea or lake (irrespective of the wave size), tidal flat, snow-covered flat plain, featureless desert, tarmac and concrete, with a free fetch of several kilometers.
2	0.005 "Smooth"	Featureless land surface without any noticeable obstacles and with negligible vegetation; e.g., beaches, pack ice without large ridges, morass, and snow-covered or fallow open country.
3	0.03 "Open"	Level country with low vegetation (e.g., grass) and isolated obstacles with separations of at least 50 obstacle heights; e.g., grazing land without windbreaks, heather, moor and tundra, runway area of airports.
4	0.10 "Roughly open"	Cultivated area with regular cover of low crops, or moderately open country with occasional obstacles (e.g., low hedges, single rows of trees, isolated farms) at relative horizontal distances of at least 20 obstacle heights.
5	0.25 "Rough"	Recently-developed "young" landscape with high crops or crops of varying heights, and scattered obstacles (e.g., dense shelterbelts, vineyards) at relative distance of about 15 obstacle heights.
6	0.5 "Very rough"	"Old" cultivated landscape with many rather large obstacle groups (large farms, clumps of forest) separated by open spaces of about 10 obstacle heights. Also low large vegetation with small interspaces, such as bushland, orchards, young densely-planted forest.
7	1.0 "Closed"	Landscape totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights; e.g., mature regular forests, homogeneous cities or villages.
8	≥ 2 "Chaotic"	Center of large towns with mixture of low-rise and high-rise buildings. Also irregular large forests with many clearings.

Stations should be sited away from the influence of obstructions such as buildings, trees, small hills, etc. and the influence of non-homogeneous surface conditions (paved or graveled areas, large open water surfaces, etc.) to the greatest extent possible. The extent to which measurements are representative on a spatial scale depends on the uniformity of the surface, topography, and on soil characteristics such as moisture, color, etc. In all cases, obvious micro-environments (tops of ridges, steep slopes, narrow valley bottoms, sheltered hollows, sites significantly influenced by diurnal atmospheric patterns, etc.) should be avoided unless the characterization of that micro-environment is the specific purpose of the weather measurements. In such cases, station site documentation (clause 7.2) should explicitly state the purpose of the measurements.

8.1.1 Wind. Recommended anemometer and wind vane exposure calls for separation distances between sensors and obstructions of a minimum of 10 times the height of the obstruction, and preferably greater than 50 times the height of the obstruction. The influence of vegetative crop growth and development through the growing season should be considered. Wind instruments are preferably mounted on top of masts, but if side-mounted on a boom, the boom length should be at least three times the mast or tower width and the boom should be mounted on the prevailing wind direction side of the mast. Instruments must be installed and maintained in a level position.

8.1.2 Air temperature and relative humidity. Generally these sensors will be co-located or integrated into one unit where one of each measurement is made at a weather station. The sensor should be protected from thermal radiation from all sources and directions using a radiation shield. Any additional air temperature sensors at other heights on the weather station should use an identical radiation shield. At a minimum, a naturally ventilated radiation shield that allows free circulation of air around all sides of the sensor should be used. The shield should be reflective (white) to avoid extraneous heat build up. The recommended separation distance between sensors and nearby obstructions is 4 times the height of the obstruction, and at least 30 m from large paved or graveled areas. Temperature/RH sensors installed on towers should be installed on booms, with the boom length equal to at least the width of the tower.

8.1.3 Solar radiation. The site should be free of obstructions above the plane of the radiation sensing element. Care must be taken that no part of the weather station structure or tower casts a shadow across the radiation sensor at any time of day or year. Reflections from nearby objects and artificial sources of radiation should be avoided. The instrument must be installed and maintained in a level position.

8.1.4 Precipitation. Rain gages should be sited on open ground with the top of the opening level and open to the sky. The separation distance between obstructions and the instrument should be at least twice, and preferably four times the height of the obstruction. Some sheltering may be desirable to reduce turbulence around the gage. Windshields can be used to reduce wind speed at the mouth of the gage.

8.1.5 Soil temperature. Soil temperature probes should be installed at the desired depths and under the desired surface conditions with soil water contents maintained at levels equivalent to the soil environment being represented (i.e., irrigated vs. rainfed). In the case of a single soil temperature measurement, it is recommended in Table 1 to install the probe under bare surface soil conditions at a depth of 0.10 m.

8.2 Measurement surface. The station should be installed over uniform, low-cover vegetation such as grass. In arid areas, natural rainfed cover is acceptable, although it may be preferable to establish and maintain a drought tolerant grass species beneath the station. The preferred installation will be over green grass vegetation having adequate soil water to support reference evapotranspiration rates. The underlying measurement surface should be homogeneous with respect to surface roughness, surface temperature, and surface moisture, particularly in the prevailing wind direction.

8.3 Fetch. The extent of the homogeneous area surrounding a station (or fetch) is traditionally recommended to be 100 times the height of the measurement above ground surface. This ″ensures″ that sensors (wind, temperature, and relative humidity) are placed within the fully adjusted layer of a newly developing internal boundary layer caused by any surface nonhomogeneities. The purpose(s) for which the weather station data is intended to be used may relax or tighten the degree to which this requirement is followed. For example, if the intended use of the weather station is for computing reference evapotranspiration, the fetch surrounding the station is recommended to be a minimum of 100 m for each 1 m of instrument height and to consist of a green, well-irrigated crop of uniform height. On the other hand, stations intended for integrated pest management (IPM) should be located in, or among, crops of interest, which might not necessarily be of uniform height or might not be well-irrigated all season e.g., orchards or groves.

LeClerc and Thurtell (1990) showed that the ″footprint″, or the upwind surface area affecting fluxes measured at downwind heights, changes dramatically with surface roughness and thermal stability. The fetch to height ratio of 100:1 may be much too small when measurements are made over smooth surfaces, or during stable thermal conditions.

8.4 Other considerations. Siting considerations should include the availability of local personnel, or cooperators, who may regularly (weekly) perform a visual inspection of station equipment, possibly carry out basic maintenance tasks, and report any problems to station operators.

8.4.1 Access. The site should be accessible by vehicle on a year-round basis for routine maintenance and calibration activities. The site should be away from roads to minimize problems of dust and vandalism.

8.4.2 Power. Automatic remote weather stations configured with the standard array of measurements given in clause 4.1 may be operated independent of any need for AC power at the site. These stations are equipped with DC power and may include a solar panel for trickle charging a rechargeable battery. Certain instrumentation beyond the standard set of measurements may require AC power at the site.

8.4.3 Telemetry. If telemetry is used for transfer of data from the remote station to a central collection facility station, siting may be constrained. For instance, if telephone telemetry is used, economics of standard telephone line installation may constrain station siting. Telephone telemetry using cellular service may eliminate some station siting constraints, however, connection and usage fees may be expensive.

For radio frequency (RF) telemetry, the proximity of the station to the RF base station, or to an RF repeater station will constrain siting. Line-of-sight between antennae of the weather station and the base station, or between the weather station and repeater station is generally recommended. This constraint becomes a necessity in the UHF band, unless stations are very close. Satellite telemetry generally imparts few siting constraints.

8.4.4 Security. Site security is a secondary, but important, consideration. When considered necessary to protect facilities and/or instrumentation, protective fencing surrounding a weather station site should not exceed 2 m in height, and should be installed to maintain the recommended separation distances for sensors given in clause 8.1.

9 Calibration and maintenance

9.1 General maintenance and calibration guidelines

9.1.1 Personnel. Only properly trained personnel should perform all maintenance and calibration activities.

9.1.2 Frequency. Routine maintenance at weather station sites should be performed on at least a quarterly basis. (See clause 9.3)

9.1.3 Spare parts. A spare parts inventory (data loggers, power supplies (battery packs and solar panels), sensors, telemetry equipment, hardware, etc.) of at least 10–15% of total equipment inventory should be maintained in ready-to-install condition. This decreases lost data and downtime by allowing immediate replacement of parts that cannot be repaired or brought into proper operation through maintenance and calibration. Also, sensors can be rotated through a laboratory-based calibration and maintenance procedure.

9.1.4 Quality control. Crucial to successful collection and retrieval of high quality data from automatic remote weather stations is the routine processing of incoming data through quality assurance and quality control (QA/QC) algorithms and the regular review of data by experienced, qualified, trained personnel. These reviews are useful for checking reasonableness of data, for flagging of unusual values, and for spotting data values showing unusual consistency or fluctuation. These reviews are preferably performed daily and are an extremely important adjunct to routine scheduled maintenance (clause 10).

9.2 Calibration tests

9.2.1 Data logging equipment. Data loggers should be rotated through a laboratory calibration procedure on an annual basis. Data loggers should be replaced and calibrated in the laboratory or by the manufacturer in the event of electrical transients, or other electrical damage to the data logger or to individual channels. I/O channels on programmable data loggers may be tested with a digital multimeter (DMM) and a program designed to test each channel.

9.2.2 Weather station sensors

9.2.2.1 General considerations. Sensor type and on-site environmental conditions will affect calibration schedules. Detailed, systematic maintenance activities and record keeping will provide considerable insight into the rates of deterioration of sensor calibrations. Physical inspections and cleaning specified in clause 9.3 can be considered a minimal level of effort to ensure sensors operate according to their calibration specifications. Sensors should not be field calibrated, but should be rotated on an annual basis from the weather station to the base for laboratory or manufacturer calibration. The preferable approach is for all sensors to be periodically rotated through a laboratory calibration procedure. Laboratory calibration involves the evaluation of current calibration coefficients and/or derivation of new calibration coefficients through the comparison of sensor output with a known standard at several (minimum of three) points across the operating range of the sensor.

Field sensor performance/intercomparison tests may be performed through accuracy tests using a known input or characteristic, or through side by side comparisons with sensors that are calibrated against a known standard (i.e., preferably against an instrument traceable to the National Bureau of Standards). These standard sensors used for side-by-side comparisons should be used sparingly and only for field intercomparison purposes. They should be either replaced periodically with new, calibrated sensors or routinely subjected to calibration against the known standard to maintain their validity. When sensors are tested side by side with calibration sensors, or against a known characteristic, simultaneous readings are taken over a specified period of time. The percent difference between the averages of the two sets of readings should be computed and compared to previously determined criteria of acceptability or rejection specific to each sensor.

$$\%\ \text{difference} = \frac{(\text{station sensor value}) - (\text{standard sensor value})}{(\text{standard sensor value})} \times 100$$

Side by side comparisons assume the standard sensor is of the same type as the weather station sensor to the extent possible.

All sensors should be subjected to calibration tests upon receipt and before field deployment to ensure proper and accurate operation.

Field tests of a new weather station as a unit should be performed immediately after installation to ensure proper operation of the system. Incoming data from the new station should be carefully screened during the first week of operation to ensure proper operation. Once a new station is operating satisfactorily, routine sensor performance tests should occur at least once a year and preferably every six months.

9.2.2.2 Solar radiation. The standard sensor should be placed at the same height and directly adjacent to the station sensor. The % difference between the two sensors should be less than, or equal to 5%. If this is not obtained, clean the station sensor and repeat the test. If the % difference is still greater than 5%, the station sensor should be replaced and subjected to a thorough laboratory calibration over a complete range of sunlight conditions. A completely opaque cover over the sensor may be used to perform a zero check.

9.2.2.3 Air temperature. Place an aspirated psychrometer at the same level as the temperature sensor in the radiation shield with the psychrometer's thermometers shaded and facing north. Compare temperature readings of the weather station sensor with readings from the dry-bulb thermometer of the psychrometer when maximum depression of wet bulb is achieved. Some difference is expected due to differences in shielding of the two temperature sensors and the fact the sensors are of two different designs.

If differences are greater than instrument accuracy specifications and the tests are being conducted under warm, calm conditions, repeat the test with the weather station sensor removed from the radiation shield, but with both sensors shaded. If the difference is still unacceptable replace the weather station temperature sensor.

Lab calibration of temperature sensors may be accomplished using a stable thermal mass of known temperature, having a time constant of more than 1 hour and design such that there are no thermal sources or sinks to create local gradients within the mass. Alternatively, calibrations may be performed against a precision laboratory thermometer in a temperature controlled water bath, or in a temperature controlled environmental chamber.

Resistance temperature devices (RTD) tend to be very stable and generally do not require calibration.

9.2.2.4 Relative humidity. Use a battery-powered aspirated psychrometer or an Assmann psychrometer (with clean wicking on the wet-bulb thermometer, wetted with distilled water, and a calibrated thermometer pair that matches ambient temperature before wetting of the wet-bulb) to obtain several readings of wet- and dry-bulb temperature. Determine relative humidity from these wet-/dry-bulb pairs using a computer or hand-held calculator program with elevation correction for atmospheric pressure or tables that can be corrected for elevation. Ensure wicking on the wet-bulb remains wet throughout the entire test. Record sensor RH values simultaneously with psychrometer readings.

Deviations of greater than 5-10% between the paired readings indicate a calibration or other problem with the weather station RH sensor. Remove the station sensor from the radiation shield and repeat test. If no improvement occurs, clean the sensor as thoroughly as possible (a few sensors allow water immersion, but subsequently require considerable time to ″dry-down″ to ambient conditions) and repeat test. If the % difference is unacceptable, the sensor should be replaced and subjected to laboratory calibration or the sensing element replaced if it is replaceable.

Lab calibrations of relative humidity sensors may be developed using saturated salt solutions, or against a standard device such as a calibrated dew-point hygrometer in an environmental chamber having temperature/relative humidity control. At least three known humidities should be used to determine a new set of calibration coefficients.

9.2.2.5 Wind speed. Place the standard sensor at the same height as the station sensor and such that there is no interference of the streams of air from the devices. The percent difference between sensor readings should be less than, or equal to, 5%. Test devices are available to drive the anemometer or propeller shaft at known rates of rotation. The station sensor should be tested at three representative rates equivalent to typical wind speeds at the station (e.g., 2, 5, and 10 m s^{-1}). The anemometer or propeller transfer function should produce a quantity (wind speed value) within one increment of resolution (0.1 m s^{-1}) of the known speed.

Starting torque of the wind speed sensor is tested with a torque wrench. If the starting torque is outside the manufacturer's specifications, the result is a higher starting threshold and loss of accuracy in determination of total wind run. Replace bearings and repeat test.

9.2.2.6 Wind direction. Upon installation, ensure station sensor is oriented to provide readings with respect to true north. Templates that resemble the faceplate of a compass can be constructed to fit around the sensor base. Oriented to true north, readings of the wind vane can be taken at each of many azimuth positions after aligning with the template (see clause 9.3.2.5).

9.2.2.7 Precipitation. Tipping bucket type gages with buckets of known tipping depth may be calibrated based on a measurement of the funnel orifice area, from which a volume of water may be computed that produces one tip of the bucket (e.g., 0.25 mm (0.01 in.) per tip).

A more reliable test is to slowly introduce a volume to produce 10 tips, or 100 tips, and to count the number of tips. Using adjusting mechanisms (set screws, etc.) typically found on most tipping bucket rain gages, it is possible to adjust the gage to operate within 1% to 2% difference.

Weighing gages should be calibrated by placing a series of known weights on the gage. The calibration of the gage should cover the total weighing range of the gage and each weight increment should be no greater than 10% of the total weighing range. The weighing gage should be protected from wind during all calibrations.

9.2.2.8 Soil temperature. See clause 9.2.2.3 for lab calibration. In-field reliability of soil temperature sensors may be checked using a laboratory-calibrated insertion type soil temperature probe of appropriate length.

9.3 Maintenance

9.3.1 Site. Perform the following maintenance during each station visit. Security equipment should be maintained in working order through visual inspection and through annual refurbishing as needed. The grounds surrounding the site should be maintained in a condition similar to the surrounding vegetation, but with the additional condition that plant growth should not interfere with operation of the sensors; this should involve weed control, grass mowing, etc. as appropriate. Trash should be picked up and removed as needed. If local personnel are available, the site should be inspected weekly.

9.3.2 Sensors. The following maintenance duties should be performed during each station visit. All leads from the sensors to the data logger should be secured to station structure (if not routed through the interior of the structure) using black UV resistant cable ties. Check the condition of wire/cable ties. Check the condition of all exposed cables and wire leads for signs of UV breakdown, mechanical damage, etc. The length of exposed cable may be minimized by pulling it through flexible plastic conduit.

9.3.2.1 Solar radiation. Carefully clean sensor surface and check instrument mount to ensure the instrument is level.

9.3.2.2 Air temperature. Clean radiation shield(s) housing the sensor. Gently clean sensor of dust, cobwebs, etc. If sensor is housed within a filter element, remove and gently clean filter.

9.3.2.3 Relative humidity. Clean radiation shield housing the sensor. Gently clean sensor of dust, cobwebs, etc. If sensor is housed within a filter element, remove and gently clean filter.

9.3.2.4 Wind speed. Clean anemometer cups or propeller vanes of dust and cobwebs. Check for dents or cracks. Check instrument level. Check anemometer starting torque for bearing condition. Simple checks such as listening for noise in bearings and/or temporarily shielding the anemometer from wind to visually monitor startup and stop responsiveness are valuable diagnostics in determining bearing fatigue and fouling. In dusty environments replace bearings semi-annually.

9.3.2.5 Wind direction. Clean sensor surfaces of dust, cobwebs, etc. Check instrument level. Verify orientation of vane relative to true north and proceed to check sensor output at a minimum of each of the four coordinate directions (N-0 or 360, E-90, S-180, and W-270). Simple checks such as listening for noise in bearings and temporarily shielding the vane from wind to visually monitor startup and stop responsiveness are valuable diagnostics in determining bearing fatigue and fouling.

Significant deviations between sensor output and known compass direction may occur when winds are predominantly from a narrow sector of the compass, this indicates the potentiometer is worn in that area and should be replaced, even though the readings from other directions may be acceptable.

9.3.2.6 Precipitation. Clean all components of gage of dust, cobwebs, insects, etc. Install screens over all ports to the interior of the gage to minimize entry of spiders and insects. Check that drainage ports are clean and functional. Check instrument level (funnel orifice opening and instrument base). For tipping buckets, ensure pulse output is received at data logger correctly for each manual tip of the bucket. Verify movement of bucket over entire range of movement. When gage is installed away from the main station structure, leads from the gage to the data logger should be buried below ground surface in a moisture- and rodent-proof conduit to prevent mechanical damage by grounds maintenance equipment and rodent chewing damage. Conduit encasement should extend above ground to the entry point of the leads to the interior of the gage and up the station structure a minimum of 0.4 m. Each end of the conduit should be sealed. If a windscreen is used, check to ensure it is level and no more than 12.5 mm above the level of the orifice, with the orifice centered within the screen.

Weighing type gages should be serviced at least once each year by washing all moving parts of the weighing mechanism with a solvent to remove grease. If the moving parts of the gage are lubricated, a dry graphite lubricant should be used. If freezing temperatures are not expected, lightweight oil with a specific gravity of 0.8 to 0.9 should be placed in the bucket to retard evaporation. If freezing temperatures or snow are expected, an oil-ethyl glycol antifreeze solution should be placed in the bucket to melt snow by chemical action, to prevent freezing of the solution, and to retard evaporation.

9.3.2.7 Soil temperature. When a sensor is installed away from the main station structure, wire leads from the sensor to the data logger should be buried below ground surface in a moisture- and rodent-proof conduit to prevent mechanical damage by grounds maintenance equipment and rodent chewing damage. Conduit encasement should extend a minimum of 0.4 m above ground at the station structure. The bare soil surface specification for this measurement (see Table 1) requires that a soil sterilant be used, or periodic weeding be performed, to keep the surface above the sensor (approximately 1 square meter) free of vegetation. A laboratory-calibrated bimetallic dial-type insertion thermometer of appropriate length(s) may be used to check sensor output.

9.3.3 Data logging and telemetry equipment. Inspect equipment during each station visit. Check all connections, plugs, etc., including wiring panel for sensor inputs, wire/cable connections to data storage device or to data telemetry equipment. Inspect data telemetry equipment as follows:

9.3.3.1 Telephone communications. The external telephone lines are the responsibility of the telephone company providing service to the site, and procedures for contacting the company when data can not be retrieved and when other potential sources of difficulty have been eliminated should be clearly established. Any internal phone lines and switching equipment (if applicable) should be inspected annually and repaired or replaced as necessary. Modems should be replaced annually and whenever data storage equipment is replaced due to damage/failure. These units should then be tested under laboratory conditions and repaired as necessary to bring them up to specifications.

9.3.3.2 RF Telemetry and satellite telemetry. Check antenna/cable (each station visit). The proper orientation of directional antennae should be verified. All cable connections at the antenna must be maintained in waterproof condition. The cable path to the transceiver should be secure. Inspect cable connections at the transceiver.

Transceiver performance should be checked semi-annually. Use a watt meter to check forward and reflected power. Take corrective action as needed to reduce any reflected power to acceptable levels. The transceiver transmit frequency must be maintained within federal agency guidelines. Check for frequency drift on the transmit side and check receive-side sensitivity. Check the power supply to the transceiver and verify it is within operational specifications for the transceiver.

Appurtenant telemetry equipment (repeaters for RF systems, base station receiving equipment, etc.) should be checked and tests performed as outlined above.

9.3.4 Power supply. During each station visit, perform the following inspections and clean and/or repair as needed.

9.3.4.1. Stations on AC power. Check all power connections. Check and verify output of power transformers with a DMM.

9.3.4.2. Stations on DC power. On stations operated with battery power and no solar panel, check for corrosion at all battery terminals and power cable connectors. Check voltage output of battery pack with a DMM. Maintain a comprehensive written record of battery replacement. On stations with battery power and a solar panel, check for corrosion at all terminals and power cable connectors. Check voltage output of battery with a DMM. Check voltage output of solar panel with a DMM (this may require connection of an artificial load to obtain realistic steady readings). Clean the surface of the solar panel. If the battery is a wet cell type, it should be housed in a separate enclosure. Check fluid levels and refill as needed. Clean and maintain the enclosure as needed. Maintain a written record of battery maintenance and replacement schedule.

9.3.4.3 Cables. Secure all power cables, ground wires, etc. to the station structure using black UV resistant wire/cable ties.

9.3.5 Station structure. Instrument support structures (towers, tripods, etc.) and instrument/electronic equipment enclosures should be inspected semi-annually and painted, repaired, and/or replaced as necessary to keep them functioning properly. Check and tighten all clamps, nuts, bolts, etc. Lightning protection in the form of fully grounded, heavy-duty lightning rods should be provided with these support structures. Support structures and the electronic equipment enclosures must be properly grounded to the lightning rods.

Maintain fresh desiccant inside data logger enclosure. Inspect the desiccant at each station visit and replace as needed with a fresh supply. Check the cable and wire ports into the enclosure to ensure they are sealed.

All cables should be secured neatly to convenient support structures using black UV resistant cable ties and protected from accidental damage by lawn mowers, etc., where necessary. Inspection for damaged or deteriorating cables should be carried out yearly, and cables should be replaced as necessary. Similarly, panels and any other electrical connection devices should be inspected annually for proper performance and maintained in a suitable state of repair.

10 Data management

10.1 Data quality assurance/quality control. Weather data collected by automatic agricultural weather stations or networks of stations should be subjected to quality assurance/quality control (QA/QC) programs for validation before dissemination or archival. A quality assurance plan of action should be formulated that contains all of the information specified in clause 7, Documentation, as well as summary documentation indicating compliance with the QA plan and appropriate updating of the recommended documentation on a regular basis.

10.2 Data validation and flagging. Data validation consists of routine review of data by experienced or trained personnel, screening of data to identify possible erroneous values, and random comparisons of data with other available data. Manual data reviews should be conducted on a frequency relative to the frequency with which data are retrieved at the central processing facility, i.e., daily reviews for data retrieved hourly or daily, etc. Data sets should be scanned for obvious incorrect values, missing data, etc.

Automatic data screening is easily performed by passing incoming data through a computer program that will check the data against specified screening criteria such as the allowable ranges for the data, historical maxima or minima, allowable rates of change, etc. Screening criteria may be based on historical data and physically realistic values. Site-specific screening criteria should be developed for each weather station. Data that do not meet screening criteria limits should be flagged for later investigation.

Data from adjacent stations should be randomly compared to assess whether instrumentation operation/calibration are changing over time. This is often done most expeditiously by using graphical techniques. Discrepancies that cannot be explained by geographic differences or regional climate variability should be flagged for further investigation.

Trained personnel should further evaluate any data flagged by the above procedures. Anomalous flagged data may be left as measured and received, but should be re-flagged with a flag indicating questionable values. Flagged data should be saved. Flagged data values that are replaced with back-up data, nearest-neighbor data, or interpolated values should remain flagged, indicating the action taken. All data changes occurring during the data validation process should be fully documented.

10.3 Data format and archival. Data storage formats for intermediate and long term storage (archival) to be used by the personnel operating a weather station, or a network of stations are not specified here due to the variety of commercial and privately developed database systems in use.

Procedures should be implemented to make all data available upon request to all potential users in a minimum of a fully documented, concise ASCII format. This documentation should include station location data (latitude, longitude and elevation); instrument exposure and deployment heights; and descriptions of the variables (order, format, units). Each record of daily data should be date stamped with the year and day of the year. Each record of data collected on a finer time scale (e.g., hourly or 15-minute) should be time stamped with the year, day of the year, and time of day.

Weather station history (site documentation, maintenance and calibration documentation, etc.) should be made available to all users upon request.

A plan for long term storage or archival of all data collected by automatic agricultural weather stations is recommended. The State Climatologist or the nearest Regional Climate Center should be contacted for advice. Archival formats and procedures are not specified here, however, procedures to produce the minimum recommended ASCII format described above should be implemented.

Annex A
(informative)

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