Chapter 9

Meteorological Systems

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1.0 Introduction

Air Quality Standards and Regulatory Modeling Application aspects of this chapter give the criteria, guidelines, and requirements for the monitoring of meteorological parameters in the State of Indiana for entry into the U.S. Environmental Protection Agency (USEPA) national database. Although the USEPA does not have regulations in the Federal Register for specific monitoring requirements, it is important that sound scientific practices be followed for meteorological data to be at its highest quality. To obtain this high quality data, the USEPA Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (as revised, March 2008)

https://www3.epa.gov/ttn/amtic/files/ambient/met/Volume_IV_Meteorological_Measurements.pdf

is used as the guiding force for this chapter.

There is an interest in, and a need for, higher quality meteorological data. Increased emphasis on models for decision-making has highlighted the need for better urban-scale meteorological data. Photochemical models, especially, have a need for a dense network of meteorological monitoring stations. The technical assistant document, "Ambient Monitoring Guidelines for Prevention of Significant Deterioration" (USEPA, 1987), requires new sources to monitor meteorological and atmospheric parameters at many proposed sites in order to evaluate the impact on air quality due to industrial growth. Additional guidance on the collection and use of on-site meteorological data for regulatory modeling applications may be obtained from the "Meteorological Monitoring Guidance for Regulatory Modeling Applications" (USEPA, 2000).

https://www3.epa.gov/scram001/guidance/met/mmgrma.pdf

This chapter of the AMB QA Manual may supersede relevant sections of the above/aforementioned Ambient Monitoring Guidelines for Prevention of Significant Deterioration" (USEPA, 1987). A committee of the American Meteorological Society (Hanna, 1977) has recommended using dispersion parameters in models that are measured directly on-site rather than use standard values from tables.

Meteorological parameters covered in this chapter are wind direction, wind speed, temperature, humidity, radiation, precipitation, and atmospheric pressure.

Separate sections covering quality assurance for ground-based remote sensing devices, as well as PAMS meteorological monitoring guidance, are included at the end of this chapter.

1.1 Micrometeorological Monitoring Applications

Section 1.0 introduced the fact that there are no specific regulations in the Federal Register for meteorological monitoring for AQS data acquisition or regulatory modeling. This is also true for micrometeorological monitoring applications.

The micrometeorological monitoring aspects of this chapter establish criteria for situations where the guidelines, primarily siting requirements for wind speed and direction, cannot be followed. These guidelines are set forth in the USEPA Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008), and from the On-Site Meteorological Program Guidance for Regulatory Modeling Applications (USEPA 1987). Most often these micrometeorological monitoring criteria will be employed in source specific monitoring events or special purpose monitoring studies where extenuating circumstances prevail.
Examples of these circumstances include:

- overhead obstructions (like high tension wires)
- funding for new equipment
- legal access issues
- site security

Every attempt should be made to follow the guidelines set forth in the previously mentioned documents (Section 1.0). Any divergence from their criteria should be well documented and reviewed by the monitoring agency's Quality Assurance Officer. When reviewing data or recommending any kind of remedial action, the deviation from standard meteorological siting guidelines (resulting in any potential bias, impact on meteorological data, and impact on criteria air quality monitoring) must be fully considered.

When circumstances (like those mentioned above) dictate that a micrometeorological site be operated in lieu of the standard meteorological (met) monitoring station outlined in Section 1.0, it is possible to interpolate the micro met wind speed data to the expected value of the wind speed at the standard USEPA recommended monitoring height (10 meters) for wind speed.

The USEPA Federal Register "Treatment of Data Influenced by Exceptional Events" (Vol. 81, No. 191, October 3, 2016)

https://www.epa.gov/sites/production/files/2016-09/documents/exceptional_events_rule_revisions_2060-as02_final.pdf

defines those events, and they can be found in total in Chapter 16, Section 3.2.1 of this Manual. For the purposes of this discussion, the following examples of Occasional Natural Events apply:

1. Sustained high wind speeds (particulate matter sampling) - This is an hourly average wind speed of greater than or equal to 18 m/s (40 mph) with light or no precipitation and dry soil.

2. Stagnation/inversions (monitoring of all pollutants) - A stagnation is a period of 4 or more days with no precipitation or no frontal passages with a wind speed less than 7.7 m/s (17 mph). An inversion is a condition in which temperature increases with altitude in contrast to the normal decrease in altitude.

To approximate 10-meter wind speeds from data gathered at a lower height, the Ground Stability Category (u), and the Wind Profile Power Law factor must be assigned.

Wind Profile Power Law Exponents for Six Atmospheric Stability Categories *(Turner 1994)*

Location	A	B	C	D	E	F
Urban (p)	0.15	0.15	0.20	0.25	0.30	0.30
Rural (p)	0.07	0.07	0.10	0.15	0.35	0.55

Pasquill Stability Categories (*Abstracted from Hanna et al. 1982*)

Surface Wind Speed (m/s)	Daytime Isolation			Nighttime Cloud Cover	
	Strong	Moderate	Slight	Thinly Overcast ≥ 4/8	Low Clouds ≤ 3/8
< 2	A	A-B	C	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C-D	D	D	D	D
> 6	C	D	D	D	D

Category A is the most unstable and category F is the most stable

The following formula can be used to approximate wind speeds at 10 meters given measured data at a known lower height:

$$u(z) = u(r)(z/r)^p$$

Where:

u(z) is the wind at height z, and z = 10 meters
u(r) is the measured wind speed at micro height, 11.1 mph
p is the wind speed profile. In this example, 0.25 (a relatively stable urban area)
r = 3 meters

Solving for u(z):

$$u(z) = u(r)\ (z/r)^p = 11.1 \text{ mph}\left[10^{(0.25)}\text{meters}/3^{(0.25)}\text{meters}\right]$$

u(z), the wind speed at 10 meters, is 14.988, or 15 mph.

Similarly, if the 10 meter wind speed is known, the 3 meter wind speed may be estimated using the same wind speed profile and atmospheric stability tables, and the same equation (albeit a different form of the equation):

Solving for u(r):

$$u(r) = u(z)\left[(r^p)/(z^p)\right] = 15\text{ mph}\left[3^{(0.25)}\text{meters} / 10^{(0.25)}\text{meters}\right] = 11.1\text{ mph}$$

u(r), the wind speed at 3 meters is 11.1 mph

When micrometeorological data are obtained in collocation with particulate samplers, or continuous gaseous monitoring, if the above approximation equals or exceeds the values outlined in the USEPA exceptional events documentation, this data should be flagged for review by the local monitoring quality assurance authority.

2.0 Siting Criteria

Proper site selection is probably even more important than selection of the equipment. From an absolute error point of view, siting of meteorological equipment is more critical than siting of other monitoring equipment. For example, poor placement of a wind direction sensor can cause errors due to obstructions changing the wind pattern near the sensor, resulting in bias data. Poor placement of any of the other meteorological sensors may also result in major errors.

This section will offer guidance in assessing the suitability of meteorological monitoring sites. Proper siting is part of the total quality control program. Of course, as in many other monitoring activities, the ideal site may not be attainable. In many urban areas, where air quality studies are traditionally performed, it will be impossible to find sites that meet all of the siting criteria. In most cases, compromises must be made. The important thing to realize is that the data will be compromised, but not necessarily in a random way. It is incumbent upon each PQAO to document site information when they perform site evaluations. In addition, the State QA Section performs site evaluations every three years which documents siting criteria. This information is saved electronically.

The primary objective of meteorological siting is to place the instrument where it can make precise measurements that are representative of the atmosphere in that area. Care must be taken since major man-made features (e.g., cities) and topographic features (e.g., mountains), can affect meteorological measurements. Even more pronounced are the effects of large natural features. Oceans and large bodies of water can affect humidity. In addition, differences in cloud cover patterns between land and water may affect temperature. Because most atmospheric properties change dramatically with height and surroundings, certain somewhat arbitrary conventions must be observed so that measurements can be compared. Secondary considerations such as accessibility and security must be taken into account, but should not be allowed to compromise data quality.

Once a site is selected, the surroundings should be thoroughly documented. This documentation would be available from the PQAO, who would keep this information either on pap;er or electronically. Documentation should include both small and large-scale descriptions, local and topographic maps (1:24,000 scale), photographs of the site, and a written description of the area that is adequately represented by this site. This last point is most important because it will allow a more rational interpretation of the data. It might state, for example, that a site adequately represents a certain section of a particular valley, the suburban part of a given city, or several rural counties. Whatever it is, the nature of the site should be described in a way that will be clear to those who will evaluate the data in the future.

2.1 Wind Speed and Direction

Wind speed and direction sensors must meet the following siting criteria (see Form 1):

1. The standard height of wind sensors over level, open terrain is 10 meters above the ground. Other sensor heights can be used, however, this must be documented accurately in the Air Monitoring Network Plan. Open terrain is defined as an area where the distance between the sensor and any obstruction is at least 10 times the height of that obstruction. An obstruction may be man-made (such as a building) or natural (such as a tree).

2. If the sensor is on a boom, the boom must be twice as long as the tower's diameter and directed into the prevailing wind. In the non-polar portion of the northern hemisphere, the prevailing dominant wind direction is essentially from the west. However, nearby geographical features such as mountain ranges, canyons, and ocean currents can have a strong influence on the prevailing wind direction of a particular site.

3. If the sensor is mounted up on a tower, the tower must be of open grid design.

4. Sensors mounted on a roof must be positioned at minimum 1.5 times the height of the building. If mounted on a tall building, the sensor must be located on a 10 to 15 foot mast on the side of the building into the prevailing wind.

5. Sensors mounted on top of a tower must be at least one tower diameter/diagonal above the top of the tower structure.

6. If a boom is used to support the sensor, it must be securely mounted so that it will not twist, rotate, or sway.

2.2 Temperature and Humidity

Temperature and humidity sensors must meet the following siting criteria (see Forms 2 & 3):

1. The ground beneath the sensor must be non-watered short grass or natural earth. In addition, the sensor should be mounted over a plot of open level ground at least 9 meters in diameter.

2. With the exception of micrometeorological monitoring, the sensor should be a minimum of 30 meters from large paved areas.

3. Large industrial heat sources, roof tops, steep slopes, hollows, high vegetation, swamps, snow drifts, standing water, and air exhausts must be avoided.

4. If the sensor is located in a louvered shelter, the height above the ground for the sensor must be 1.25 to 2 meters. In addition, the shelter must be oriented with the door opening toward true north.

5. If the sensor is mounted on a boom, the boom must be as long as the tower's diameter or diagonal distance.

6. If the sensor is mounted on a tower, the tower must be of open grid design.

7. Temperature sensors must have a downward facing aspirated shield. If not, the aspirator shield must point to true north.

8. The distance between the sensor and any obstruction must be at least 4 times the height of the obstruction. An obstruction may be man-made (e.g., a building) or natural (e.g., a tree).

2.3 Solar Radiation

Radiation sensors must meet the following siting criteria (see Form 4):

1. The sensor must be free from any horizontal or vertical obstruction.

2. The sensor must be away from light-colored walls.

3. The sensor must be away from artificial sources of radiation.

4. Pyranometer sensors should be located on a tall platform or roof so that there is an unrestricted view of the sky in all directions during all seasons.

5. Net radiometers should be mounted about 1 meter above ground.

2.4 Precipitation Gages

Precipitation gages must meet the following siting criteria (see Form 5):

1. The mouth of the gage must be mounted horizontally.

2. The gage must be located at a minimum of 30 centimeters above ground and should be high enough to avoid water splashing in from the ground or the gage being covered by snow. In addition, the collector should be heated if necessary to properly measure frozen precipitation.

3. The surface area around the gage must be natural vegetation or gravel.

4. If the gage is located in an open area, a wind shield should be used.

5. The gage must be positioned at a minimum of 100 meters from open storage of agricultural or fuel products and from mobile pollution sources.
6. The gage must be placed away from overhead wires that could obstruct the rainfall from going into the gage.
7. Wet/dry collectors must be oriented parallel to the prevailing wind with the wet bucket upwind of the dry bucket.
8. The gage must be positioned at least 2 times the height of any obstruction.

2.5 Atmospheric Pressure

No siting criteria exist for the measurement of atmospheric pressure; however, care must be taken to not expose the pressure sensor to anything that could interfere with the measurements. The sensor is sensitive to both the atmospheric pressure (weight above the station) and wind pressure.

2.6 Micrometeorological Monitoring Applications

Micrometeorology monitoring might be defined as monitoring performed with deliberation, outside optimum siting criteria. This may be done for purposes of expediency (perhaps in an emergency response application), or for special purpose short term studies where the financial expenditure of a permanent conventional meteorological station is not practical. Micrometeorological monitoring may also be considered more appropriate in situations that are meant to be short term or quantitative.

The area of representativeness of a micrometeorological site will almost always be smaller than that of a conventional met station and this must be taken into consideration. Objects that do not constitute obstructions at standard measurement height (10 m) might affect micrometeorological monitors. As a result, it may be necessary to have more than one micro meteorological site to fully evaluate meteorological monitoring conditions within a specified area of concern.

Once a site has been chosen for a micrometeorological application, exacting documentation will be required to define and evaluate the represented area of interest. This should include large and small-scale descriptions with local and topographical maps, photographs, and a written description of the area. If possible, Global Positioning System (GPS) or Universal Transverse Mercator (UTM) coordinates should be included.

2.6.1 Wind Speed and Direction

In micrometeorological monitoring applications, wind speed and direction sensors must meet the following siting criteria (see Form 1):

1. The height of a wind sensor is below 10 meters (usually 2 to 3 meters) above ground over open level terrain. Open terrain is defined as an area where the horizontal distance between the sensor and any obstruction is at least 10 times the height of that obstruction. An obstruction may be man-made (building) or natural (tree). In many cases, open terrain for micrometeorological monitoring will be a difficult criterion to meet. Even small elevations /indentions of the ground level can cause eddies and wake areas which might bias wind data. Therefore and once again it is critical to clearly identify the topography of the sampling locale and include in the site description such characteristics as:

    - valleys
    - hills
    - bodies of water
    - roadside ditches
    - hedgerows
    - dumpsters
    - out buildings

2. If it is necessary to locate a ground mounted sensor near a building, it should be mounted on the historical upwind side of the building. If the sensor must be located on the historical downwind side, it should be at a distance of at least 10 times the height of the building. A 'wind milling' of the vane may occur if sensors are located too close to buildings. This causes the speed sensor to measure exaggerated gusts. As a general rule, air flow around a structure is disturbed to twice the height of the structure upwind, and six times the height downwind.

    If historical wind data are unavailable, dominant wind direction may be determined using flags, smoke tubes, soap bubbles or by temporary installation of the direction sensor.

3. If it is necessary to put a sensor among vegetation, locate it equidistant from the tallest trees or shrubs.

4. When choosing a site, consider locations that have large portions of similar surface roughness lengths. These sites will yield data which will be representative of a greater area. Surface roughness lengths in meters or centimeters are a measure of the near surface wind resistance.

Sample Surface Roughness Lengths
(USEPA Office of Air Quality Planning and Standards)

Surface Type	Surface Roughness Length (cm)
Smooth Desert	0.03
Grass (4cm)	0.14
Grass (5-6cm)	0.75

Wheat	22.00
Fir Forest	283.00

Additionally, atmospheric stability will have an indirect effect on wind speed and direction. When the sun heats the earth's surface, the air is also heated, increasing the thermals and consequently increasing the mixing of surface and upper air. Since upper air masses normally have more energy (higher winds), this mixing in turn increases the speed at ground level. The opposite is true as the earth's surface temperature decreases at night. If the area of interest lies in a valley or strongly sloped area, the cooled air can drain to the lower level. These 'drainage winds' can be strong and will increase as the night continues to cool, thus affecting the measured speed. Therefore, it is important to site sensors centrally in a valley area, and to avoid placing them at the base of a hill.

2.6.2 Temperature and Humidity

Temperature and humidity sensors must meet the siting criteria stated in Section 2.2 (See Forms 2 & 3).

2.6.3 Solar Radiation

Radiation sensors must meet the siting criteria stated in Section 2.3 (see Form 4).

2.6.4 Precipitation Gages

Precipitation gages must meet the siting criteria stated in 2.4 (see Form 5).

2.6.5 Atmospheric Pressure

See Section 2.5.

3.0 Wind Speed and Wind Direction Measurement

Wind measurements are of primary importance in the diffusion and transport of atmospheric pollutants. These measurements include wind speed, wind direction, and turbulence or gustiness. There are many wind-measuring systems commercially available. Some are ruggedly constructed, designed for a wide range of applications, and require minimum attention. The more delicate instruments, such as those used for measuring small-scale turbulence, can only be used during periods of favorable weather.

Almost any anemometer or wind vane will provide some information on wind characteristics. However, the quality of wind data depends directly upon how well the sensor is maintained and how the measuring equipment functions as a system. Not only must the dynamic characteristics of the sensor match program data requirements, but the sensor must also interface without degradation of important performance characteristics with the total data acquisition system, which may include the transducer, signal conditioner, telemetry, data processor, and readout device.

3.1 Types of Sensors/Instrumentation

1. Anemometers - A number of wind speed sensors operating on a variety of physical principles are available commercially. The rotational cup and propeller anemometers are the most commonly employed wind speed sensors. Some sensors, called sonic anemometers, use ultrasound to determine horizontal wind speed and direction. This type of sensor’s measurement is based on transit time, the time it takes for the ultrasound to travel from one transducer to another. Sensors with other designs are generally used in specialized studies.

2. Wind Vanes - Wind-direction-measuring sensors are operated by wind exerting pressure on a surface that rotates about a fulcrum. The standard wind vane measures only the horizontal wind direction, but a bi-directional vane is free to move through 360 degrees horizontally as well as ±50 degrees or more from the horizontal. The shape and design of the vane surface may vary with the manufacturer. As with the wind speed, the ultrasound sensor will also measure wind direction.

3. Combination Wind Sensors - Two types of sensors incorporate direction and speed measuring capability in a single mechanical device. The propeller vane sensor measures two-dimensional wind (horizontal) and the propeller bi-vane sensor measures three-dimensional wind (horizontal and vertical).

4. Wind Component Anemometers - These can be used to determine the wind speed and direction(s), using simple trigonometry. These instruments include the x, y, z prop (often called u, v, w), the sonic, the vortex shedding, and the ion flow anemometers.

5. Transducers - Transducers convert the parameter being measured by a sensor into an electrical signal. This chapter will discuss transducers used in rotation-type wind speed sensors and vane type direction sensors only.

The rotary motion of wind speed cups and propellers is most often converted to a voltage or a frequency. Both alternating current (AC) and direct current (DC) generators are used, but the latter is used more often. Frequency-type devices, sometimes called light choppers, have advantages in that they are almost frictionless, operate at lower wind speeds, and produce signals that can be transmitted without loss over long distances. Typically, this type of transducer is made to interrupt the light of a Light-Emitting Diode (LED) at a rate of 1 to 132 times for each rotation of the sensor. Units that interrupt the light once per revolution of the anemometer shaft are usually used to measure wind run (the distance or length of flow of the air past a point during a given interval of time), thus producing longer time averages. A single sealed glass switch, used in combination with a magnet on the shaft of the anemometer, is also a frequency-type transducer for wind speed or wind run. Another frequency-type device now used in anemometers is the Hall-effect generator. This works using electrical polarization of a conducting plate moving through a magnetic field. Mechanical anemometers with wiper-type contacts, still in use for climatological studies, are attractive alternatives because of their simplicity but are of limited use in pollution studies.

Wind direction transducers are of several basic types: wiper or sealed contact switches, single or double potentiometers, and DC or AC synchronous motors. Some of the more sophisticated transducers operate on the principal of capacitance with outputs in frequency form. Wire-wound and carbon-deposited potentiometers are used most frequently.

6. Signal Conditioners - In most electronic systems, the signal from the meteorological parameter being measured is transmitted from the transducer to a signal conditioner or readout device, with power applied at some or all of these steps. The signal conditioner converts the transducer output into an electrical quantity suitable for the proper operation of the readout equipment whether it is a chart recorder or a data acquisition system. The signal conditioner may vary from a simple resistance network or impedance-matching device to an amplifier, an analog-to-digital converter, or, as in the case of the photoelectric speed transducer, a frequency-to-voltage converter. Signal conditioners are devices that convert from 360 to 540 degrees of wind direction and provide "average" wind or wind with "time-weighted" average. Scalers that compress, expand, or change the transducer signal from electrical to engineering-equivalent units are also signal conditioners.

7. Readout Devices - Digital displays are popular for logging and displaying wind data. They come in a wide range of designs and are usually elaborate systems that include analog-to-digital conversion, integration over specified intervals, and memory or storage capability. The output format of these systems should be compatible with the computer used for data processing. The data generated provide the user with better accuracy compared to data reduction from strip chart recorders.

Direct writing (D'Arsonval movement) galvanometric recorders with strip charts are used frequently for wind measurements. They are used because of their reliability and their speed of response. The chart drive mechanisms are available as hand-wound, spring-driven, battery-powered, or AC powered. It is important to select a recorder in which the damping characteristics of the galvanometer do not degrade the response of the sensor and are in compliance with the frequency response required in the study. Most galvanometric recorders used for wind measurements are continuous curve-tracing recorders. The chopper-bar type, designed to make an imprint on pressure-sensitive paper each time the meter pointer is clamped against a sharp-edged platen, produces a record that is non-continuous. Imprints are usually made every 2 seconds, so in rapidly varying winds the record appears scattered. Some manufacturers of meteorological instruments supply a recorder with a built-in signal conditioner that reduces the scatter through the use of either unspecified or selective time constants on the response of the galvanometer. This conditioner must be closely evaluated if calculation of the standard deviation of the measurement is an objective in analyzing the record.

Potentiometric recorders, used frequently for wind measurement, may not have the rapid response characteristics of galvanometric recorders. However, as a null-device, the input impedance is high when the stylus is at equilibrium; therefore, errors due to electrical loading of the sensor output and errors due to voltage drops in long signal leads are minimized.

Multi-point potentiometric recorders, which sequence through a series of inputs of scheduled cycles, must not be used for recording wind. Instantaneous samples of wind direction or wind speed once every few minutes are of little use for most air pollution investigations. Curve-tracing potentiometric recorders are useful and are available with charts that require ink or with inkless charts that operate with a heated stylus.

3.2 Wind Sensor Characteristics

1. Cup Anemometers - These anemometers have complex-shaped cups. The net torque (lift greater than drag) causes a rate of rotation roughly proportional to wind speed. The cups respond to any horizontal wind direction, which is an advantage, but they are also responsive to the vertical component of the wind. In turbulent flow, the output (average speed) may be closer to the total speed than to the presumed horizontal component (MacCready, 1966). The design of the anemometer cup assembly and the material from which it is constructed are important in determining the starting threshold, dynamic response, linearity, and durability of the instrument. The ratio between cup diameter and cup wheel diameter influences the calibration curve (Gill, 1973). Starting threshold is defined as the lowest wind speed at which the rotating cups meet the accuracy specifications (Lockhart, 1970). In order to define the smallest eddy size to which cups will be responsive, a dynamic characteristic known as the "distance constant" must be known. This is determined in a wind tunnel by measuring the time for the cups to reach 63 percent of the tunnel speed after being released from a non-rotating condition. The distance constant in meters may be expressed as a time constant in seconds at a given wind speed by dividing by that wind speed in meters per second. USEPA does not specify a distance constant for anemometers. USEPA does suggest a distance constant of <5 meters at 1.2 kg/m. The reason why the distance constant is included is to urge users to buy high quality responsive sensors. Heavy sensors with long distance constants are more likely to produce over-speed errors, which overstate the average wind speed. If they are used to measure turbulence, they will underestimate sigma theta (standard deviation of the wind direction) because of a failure to respond properly to eddy sizes smaller than twice the distance constant.

2. Propeller Anemometers - Propeller anemometers, especially helicoid types, are sensors with rotation rates linearly proportional to the wind speed over a wind speed range (Gill, 1973). Propeller anemometers must be oriented into the wind. The error from the failure of the vane to perfectly orient the propeller is small since propellers have a nearly cosine response, i.e., the propeller turns at a rate almost directly proportional to the wind component parallel to its axis. Like the cup anemometer, the propeller anemometer is a first-order, non-oscillatory system whose dynamic characteristics can be described by the distance constant referenced above. Fixed axis propeller anemometers are designed to measure two or three components of wind simultaneously at a point in space. They represent a special type of propeller anemometer for the direct measurement of turbulence (Fill, 1975). Three helicoid anemometers in an orthogonal array measure the wind for the axes u-v-w. Each propeller turns at a rate almost proportional to the wind component parallel to its axis. Cosine response, although not yet perfected, is critical in this equipment. However, this device does

not have the static balance (a two axis wind vane), which is also used for the turbulence measurements. Under conditions of rain, snow, and heavy dew, the bi-vane imbalance may produce unacceptable errors.

3. Wind Vanes - Wind vanes have a damped, oscillatory motion. This characteristic second order response is the result of such factors as weight of materials, shape and size of vane, and location and weight of counter-balance. One indication of the performance of the vane is the starting threshold. As described by Finkelstein (1981), this is the lowest speed at which a vane released from a position 10 degrees off the centerline in a wind tunnel moves to within 5 degrees of center. There are several dynamic characteristics, identifiable as constants, which can be used to define the performance of a wind vane (MacCready, 1965, and Wieringa, 1967) in response to a step function. These include damping ratio, damped wavelength, undamped wavelength, and delay distance. Undamped wavelength is used in determining the dynamic response of a wind vane to sinusoidal wind direction fluctuations (varies to a sine curve).

4. Damping Ratio - The damping ratio is a constant that is dimensionless and independent of wind speed. It is calculated from the relative amount of overshoot on each of two successive half cycles of a decaying oscillation. The overshoot, ε, and damping ratio S is calculated from the equations:

$$S = \frac{\ln(1/\varepsilon)}{\{\pi^2 + [\ln(1/\varepsilon)]^2\}^{1/2}} \qquad \varepsilon = 2_{(n+1)} / 2_n$$

Where $2_{(n+1)}$ and 2_n are the amplitudes of the n and n+1 deflections respectively.

For most operational programs, a damping ratio of 0.4 or greater is recognized as satisfactory.

5. Damped Wavelength - The damped wavelength is easily determined by multiplying the time for one complete oscillation by the wind speed in the wind tunnel.

6. Delay Distance - Delay distance is another observed measure of the response of a vane to a step change. Delay distance is based on the time required for a vane to reach 50 percent of the distance from an initial displacement, to 10 degrees toward the centerline on the first swing. This is multiplied by the tunnel speed to obtain the delay distance.

7. Sonic Anemometers - Sonic anemometer systems are based on the principle that wind changes the transit time of a sound pulse across a fixed distance. Sonic systems can be designed in two dimensions for horizontal wind speed and direction as a replacement for the cup and vane or propeller units, or in three dimensions for both horizontal and vertical wind measurements. For those applications where the contribution of small eddies is important, sonic systems are an excellent choice.

3.3 Wind Data Requirements

Any data requirement should be expressed in the context of all applications for which the data may be used. Wind data are used in environmental monitoring for source location, transport and dilution modeling, and as a diffusivity indicator. The principal specifications are dynamic range (most important is the threshold) and dynamic performance (distance constant for speed and damping ratio and delay distance for direction). It is also important to specify the averaging time and method in order to judge the adequacy of the measuring and recording system. For most atmospheric dispersion studies, a starting speed (the speed required to start motion of the sensor) of 0.5 m/s or less is appropriate for both vanes and anemometers. Wind vanes should have a damping ratio of 0.4 or greater and a delay distance of 5 m or less. Anemometers should have a distance constant of 5 m or less. For climatological studies, less sensitive instruments may be used.

Averaging for wind speed may be done by scalar methods (dilution) or vector methods (transport) and should represent one hour. Wind direction should be averaged by obtaining the resultant vector direction for the hour. Sigma theta should represent 3 to 10 minutes if stability categories are to be selected, but should represent the hour when the preferable direct calculations are made for diffusion (Strimaitis, 1981).

3.4 Procurement

For research projects it might be possible to purchase instruments with better specifications or of more recent design. But in operational programs, only field-tested and time-proven instruments with known performance records should be purchased.

Caution should be used in purchasing components as opposed to total systems. It is important to match the dynamic characteristics of the wind sensors and the electrical characteristics of the transducers with the readout device. For digital systems, special attention should be given to sampling and averaging times as well as instantaneous, as opposed to integrated, data acquisition.

3.5 Acceptance Testing

The supplier should provide all calibration certification data for the equipment, including curves and specifications. A table or formula should be provided which relates the rate of rotation of the anemometer shaft (or frequency for light-chopper sensors if the number of pulses per revolution is also given) to wind speed (or output voltage given to a voltage to speed range relationship). This formula or table will usually relate to a nominal propeller or cup. The specific propeller or cup assembly should have a permanent identification code (serial number). In those cases when wind tunnel calibration data are provided, this identification is required.

The acceptance test for the direction vane should include a measure of how well the sensor represents the relative position of the vane to the sensor housing. Four points 90 degrees apart can be easily bench-tested by drawing perpendicular lines crossing at the vane rotation axis and holding the vane shaft parallel to the lines. The manufacturer's method of coping with the discontinuity between 360 degrees and 1 degree should be checked to ensure that the method meets specifications.

3.6 Calibration

Calibration for wind speed and wind direction may be performed using several methods. However, specific dynamic response characteristics such as threshold speeds, damping ratios, delay distances, and distance constants can only be checked in a wind tunnel. Instruments should be returned to the manufacturer or a properly equipped wind tunnel facility for this type of calibration check. Sonic anemometers should be returned to the manufacturer for calibrations. In addition, prior to any calibration adjustments, the operational period must be verified.

1. Wind Speed - Calibration of wind speed sensors will normally be performed using a certified synchronous motor or a certified selectable speed anemometer drive. Other methods for calibration may include using a photo tachometer, number of turns per minute, or by using a calibrated collocated sensor. These other methods introduce more error and may not be as convenient as using the synchronous motor or selectable speed anemometer drive. Therefore, it is recommended that a synchronous motor or selectable speed anemometer drive be used. This synchronous motor/selectable speed anemometer drive must be certified against the Quality Assurance Section's photo tachometer annually to ensure the revolutions per minute (rpm) are accurate. The calibration can be performed when the sensor is on top of the tower or the sensor may be removed from the tower and the calibration performed at ground level. The calibration must include a zero check and at least 2 different speeds. One speed should represent low wind speed (e.g., within 10 mph) and one at high wind speed (e.g., at least 20 mph). In order to use the synchronous motor or selectable speed anemometer drive, the cups or propeller will need to be removed. The cups or propeller must be inspected for any type of damage that could alter the wind speed. If any damage is apparent, the data collected will be suspect and the sensor should not be used until repairs are made. The conversion of rpm to mph will depend on the type of sensor. The formula for this conversion should be available in the sensor's maintenance book. A torque test is recommended to determine the wind speed needed for the sensor to respond.

2. Wind Direction - The calibration of wind vanes will consist of aiming the vane at a known direction, performing a bench linearity check, and a torque test. A telephone pole or any other distant object that will remain stationary could be used as the reference point once the degrees from the vane to this reference point are determined. The degrees to and from the object can be determined by several methods. An acceptable method of establishing true north is by the location of the sun at true solar noon. Another acceptable procedure for determining true north involves shooting the North Star with a first-order theodolite. Any textbook or handbook on land surveying will describe the technique and contain all the necessary tables. Another method for determining true north involves using a magnetic compass. However, caution should be used so that the magnetic compass is not influenced by the strong permanent magnet in the wind recorder, iron metal objects, or the electromagnetic field. Do not forget to allow for magnetic declination from true north. In

addition, alignment in the vertical is equally important. Studies have indicated that vertical misalignment of 1 degree may yield data errors of 10 percent or greater in measurement of turbulent parameters (Pond, 1968; Deacon, 1968; and Kraus, 1968). Vertical alignment should be established with a good carpenter's level or torpedo level at two points that are 90 degrees apart in the horizontal. Factory calibrated sonic anemometers should be attached securely and aligned 180 degrees from true north, using any of the methods described above.

The bench linearity check involves moving the vane in known degree increments, such as advancing the vane exactly 90 degrees for every point and waiting for the response to stabilize, and recording the degree output. Enough increments should be used to include the full scale of the sensor (this will allow all potentiometers to be evaluated). A torque test is recommended to determine the wind speed needed for the vane to respond. There will be a bias to the direction recorded due to the wind vane not pointing in the correct direction at the recorded time (see Form 7) if the torque test fails.

3.6.1 Frequency

Calibrations must be performed at least annually for State/Local Air Monitoring Station (SLAMS) sites, semi-annually for National Core multi-pollutant monitoring stations (NCORE) and Photochemical Assessment Monitoring Stations (PAMS) sites, and quarterly for PSD sites. In addition, calibrations must be performed if the sensor fails an audit or if the sensor is damaged and repaired. Sonic anemometers should be sent to the manufacturer on an annual basis or if the unit is damaged or fails an audit.

3.6.2 Limits

1. Wind Speed - Calibration limits for wind speed are ±0.50 mph up to 10.0 mph and ±5% if the speed is >10.0 mph. If these limits are not met, the sensor will require maintenance and another calibration until these limits are met. In addition, the sensor must respond within the torque limit. The torque limit will depend on the type of sensor and should be found in the sensor's maintenance manual. The data collected from an out-of-calibration sensor are invalid back to the previous audit or calibration, or if it can be determined by analyzing the data when the unit malfunctioned.

2. Wind Direction - Calibration limits for wind direction are ±5.0 degrees when the vane is pointing to a standard reference point. In addition, a bench linearity check must be made with no more than a 10.0 degree spread between the highest negative and highest positive difference between the response and the known degrees. If either one or both of these calibration checks fail, maintenance is required and both checks must be repeated. In addition, a torque test is recommended. The data collected from an out-of-calibration sensor are invalid back to the previous audit or calibration, or if it can be determined by analyzing the data when the unit malfunctioned.

3.7 Preventive Maintenance

Preventive maintenance of the equipment should be performed as often as possible; at least monthly. These checks include an examination of the sensors and the readout equipment. At locations where pollution is heavy, it may be necessary to routinely change the bearings in both the anemometer and vane housing. Oil-less bearings should never be oiled. Bearings can be checked with a torque gauge. Recording equipment with pens and ink should be cleaned on a regular monthly schedule. If the recorder is equipped with disposable felt tip pens, they should be checked for proper operation. The fluctuations of the wind, as recorded by the pen, result in an average pen life of 2 or 3 days, so there may be a loss of data if checks are not frequent enough.

Light freezing rain with little wind is very detrimental for cups and especially for propellers. It has been found that a light spray of "Pam" (a household substitute for grease) or an equivalent non-sticking spray helps to retard the formation of ice, especially on propeller anemometers. For extremely low temperature conditions, the use of external heat lamps or heater strips is helpful in stopping ice formation. Internal heaters, available with some wind sensors, keep bearings free but have low wattage and are of limited use in severe conditions. Spare parts for anemometers and vanes should include replacement cup assemblies or propellers, vanes, and bearings. A log should be kept of all preventive maintenance activities.

3.8 Audits

1. Wind Speed - An audit for wind speed consists of repeating the calibration procedure without making any adjustments. The audit must provide enough information to determine the validity of the data. Any of the methods mentioned in Section 3.6 may be used to perform the audit, but a synchronous motor/selectable speed anemometer drive is preferred. The torque test is optional for the audit (see Form 8).

2. Wind Direction - An audit for wind direction consists of repeating the calibration procedure without making any adjustments. The audit does not require every calibration check. The linearity check is optional for the audit, but the vane must be challenged with at least 2 reference points (e.g., the primary reference point, and a 180 degree swing from the primary reference point). The bench check and torque test are optional for the audit, but may be helpful in determining the condition of the sensor (see Form 9).

3. Ultrasonic units – A propeller/vane unit is installed near the ultrasonic unit for approximately one week. The data is analyzed to ensure reasonable comparability between the ultrasonic unit and the QA unit to determine the validity of the data.

3.8.1 Frequency

Audits for wind speed and wind direction must be performed once a year. Ideally an audit should be performed 6 months after a calibration. This will allow the sensors to be evaluated twice a year. If a problem does occur, the amount of data which would be affected will be limited.

3.8.2 Limits

All wind speed and direction audit limits are the same as the calibration limits.

4.0 Temperature

Temperature is not simply an isolated piece of meteorological data, but it is used in the measurement and determination of a number of other atmospheric parameters such as vertical temperature gradient (stability), relative humidity, and gaseous pollution concentrations. Several types of sensors and recorders are used routinely in a variety of combinations to acquire temperature data. The temperature sensors listed below are used most often for environmental measurements.

4.1 Types of Sensors/Instrumentation

1. Linear Thermistors - Thermally sensitive resistors or thermistors are electronic semiconductors that are made from metallic oxides. The resistance of a thermistor varies inversely with its absolute temperature. Linear thermistors are a composite of two or more thermistors and fixed resistors designed to produce a linear response over a wide temperature range. In system configuration, the thermistor is connected to a bridge circuit or some suitable signal conditioning circuit. When a low voltage is applied to the thermistor, the output from a bridge circuit is a voltage that varies directly with the temperature of the sensor. Linear thermistors are particularly well suited to remote sensing applications because of their ratio of resistance change to temperature change. Coefficients on the order of 125 ohm/degree Celsius are common (Lockhart and Gannon, 1978), reducing the impact of lead resistance errors. A lead resistance of 12.5 ohms would be required to produce a 0.1 degree Celsius temperature measurement error. The thermistor or thermistor composite may be packaged as a glass-covered bead or encased in a stainless steel sheath. The latter is common and best for monitoring applications.

2. Resistance Temperature Detectors - A Resistance Temperature Detector (RTD) operates on the principle that the electrical resistance of a pure metal increases as temperature increases. RTD sensors are made using silver, copper, nickel, and platinum wire. Platinum wire is the best material to use because of its superior linearity and stability characteristics, high sensitivity, and resistance to corrosion. The RTD probe is encased in a protective stainless steel housing composed of an insulating core wrapped with platinum wire. The resistance of the wire is measured using a bridge circuit and a signal conditioner.

   The RTD operates at a much lower resistance to temperature ratio than the linear thermistor. RTDs used most often in meteorological work have a coefficient of resistance change on the order of 0.4 ohms per degree Celsius and are more sensitive to lead resistance errors than are thermistors. "Three wire" and "four wire" systems are configurations that automatically compensate for lead resistance.

3. Liquid-In-Glass-Thermometers - Most of these thermometers are 10.5 inch 10 gram glass tubes with a uniform capillary bore and a liquid reservoir or bulb at the bottom. Thermometers are usually mounted on a stainless steel back with the bulb protruding to allow free air circulation. Volumetric expansion and contraction of the operating liquid provides the measure of temperature. The liquid is usually mercury but may be a mixture of ethyl alcohol and red dye. Thermometers filled with alcohol are called spirit thermometers. Though inherently less accurate than a mercury thermometer, the spirit thermometer must be used where extremely cold temperatures are anticipated because mercury will freeze at -38 degrees Celsius.

4.2 Sensor Characteristics

4.2.1 Accuracy

A high-quality mercury thermometer, properly calibrated, will provide temperature data of sufficient accuracy for most atmospheric measurement programs. Over the years, the capillary bore will tend to contract slightly, causing the zero point to rise. Because the thermal response of mercury is essentially linear, this error is correctable through calibration. The most serious errors incurred in using a mercury thermometer are usually due to improper exposure and/or observer error (e.g., parallax error in reading the temperature). Typical commercial platinum RTD sensors follow the platinum characteristic that represents a resistance accuracy of ±0.26 degrees Celsius at 0 degrees Celsius and ±0.38 degrees Celsius at 50 degrees Celsius. Linear thermistors are available commercially with an accuracy of ±0.15 degrees Celsius over the range of temperatures normally encountered in environmental measurements (Lockhart and Gannon, 1978). Ordinary commercial thermocouples are only accurate to ±1 degree Celsius (Wang, 1975). Accuracy of a measurement system is limited more by such factors as sensor exposure, improper coupling, and signal interference than by accuracy of the sensor. For air quality monitoring applications, an accuracy (including coupling error) of better than 0.5 degrees Celsius is easily achievable and adequate (Strimaitis, 1981).

4.2.2 Linearity

There are no linearity problems with any of the electronic or liquid-in-glass sensors within the extremes of tropospheric temperature. Some linearity problems occur in the deformation-type sensors, particularly at extreme temperatures.

4.2.3 Response Time

A certain amount of caution must be exercised when assessing the value of quick response time in taking stationary environmental temperature measurements. At the warmest time of the day, a continuous temperature trace may show variations of up to 1 degree Celsius in a 30-second period. Care must be taken in evaluating instantaneous temperature data from a thermistor or RTD, both of which may have time constants as short as 5 seconds or less. For both of these sensors, temperature values should be the average of a series of readings taken over a minimum period of 1 minute to avoid "noise" errors. Usually the stainless steel sheath, which protects the sensitive element for field monitoring use, adds to the time constant mechanically thereby providing both ruggedness and a more useful time constant.

4.2.4 Precision

Most good quality electrical temperature systems used for monitoring in the atmosphere will have an output with better resolution and precision than accuracy. The application of the data may take advantage of this fact. For example, a temperature difference between two levels on a tower may (and should) be calibrated around the precision of each sensor, yielding an accuracy of a difference on the order of the precision of the sensor (0.1 degree Celsius for example). This statement must be qualified to either ignore the coupling error or assume each sensor will suffer the same coupling error and, therefore, not influence the difference measurement. The latter is a reasonably good assumption when identical radiation shields are used.

The accuracy of the temperature differential measurement system, excluding coupling errors, may be as good as the resolution or precision if the effort is made to either adjust the circuits or correct the data to achieve it. The nominal values quoted above reflect interchangeability with circuits adjusted to the nominal values given in the manufacturer's manual. Given sensor stability, the accuracy will be as good as the calibration.

4.2.5 Durability

All of the electronic temperature sensors are fairly rugged and stable. Liquid-in-glass thermometers obviously require careful handling. The deformation thermographs also require delicate handling as any physical damage will alter the calibration.

4.2.6 Radiation Shields

The most serious temperature measurement problem encountered in environmental thermometry is radiation error, which can amount to several degrees Celsius at midday. Early attempts to combat radiation error took the form of instrument shelters, such as the all wood, louvered, double roofed cotton region type. Much better results in reducing radiation error have been achieved with aspirated radiation shields.

1. Naturally Ventilated Radiation Shields - The most common type of the naturally ventilated radiation shield employs a vertically mounted sensor with a 360 degree ventilation exposure. The housing is topped with single or multiple polished domes for solar radiation shielding and has lower circular shields to block terrestrial and reflected radiation. The vane oriented radiation shield directs the ambient wind to the temperature sensor. A swivel mounted, white, horizontal, double walled tube is equipped with a large vane that keeps the housing opening pointed into the wind. Unfortunately, these shields allow large errors when the wind is light. Both of these naturally ventilated radiation shields will accept a variety of electronic temperature sensors, including the thermistor, thermocouple, and RTD.

2. Mechanically Aspirated Radiation Shields - Mechanically aspirated radiation shields can be used where power is readily available to drive the blower. The motor draws ambient air across the sensor at an average flow of 5 m/s. The radiation shield may take a number of forms, but common features include double-wall construction and white paint. Some use thermos bottle type wall construction. Some are mounted horizontally with the air intake facing north, while on others, the tube is mounted vertically with the air intake facing downward. Some vertical units also employ domed polished radiation shields for both sky and ground radiation shielding (McTaggart-Cowan and McKay, 1976). These mechanically aspirated radiation shields will accommodate the full range of electronic temperature sensors along with a variety of dew point and humidity sensors. It is desirable that blowers be wired to signal whether or not they are operating, particularly in tower installations.

4.3 Temperature Data Requirements

In general, measuring temperature with accuracy greater than 0.5 degrees Celsius may not be necessary. Extreme daytime horizontal temperature gradients have been documented (Hoffmann, 1965, and Department of the Army, 1975). Certain circumstances require more accuracy or relative accuracy for differential temperature measurements. For example, a temperature gradient measurement requires a relative accuracy of temperature or an absolute accuracy of temperature difference of 0.1 degrees Celsius. This is true for the low level, local surface gradient measurement between 2 meters and 10 meters above the ground or for the more conventional measurement between 10 meters and 60 meters. Also, if humidity is measured by the wet-bulb and dry-bulb difference, sensors should be matched so that small differences are meaningful. The atmosphere is a turbulent, differentially heated fluid should remind any investigator that a temperature recorded to the nearest tenth of a degree is representative of only a small volume of air for a very short period of time. All routine monitoring applications of temperature data will be expressed as a long-term average such as in 1-hour increments.

4.4 Calibration

Temperature sensors may be calibrated in the laboratory but must be calibrated in the field after the sensor is installed. Performing both an in-house and then a field calibration may provide better precision and accuracy from the sensor; however, only the field calibration is required. The calibration must consist of submerging the sensor into a water bath or a calibration chamber. In addition, a check should be made after the sensor is placed in the shelter. The sensor must be compared against a thermometer that is traceable to a National Institute of Standards and Technology (NIST) thermometer or some other temperature transfer standard. The NIST-traceable thermometer should be graduated in 0.1 degree Celsius increments. In addition, prior to any calibration adjustments, the operational period must be verified.

4.4.1 Procedure

The sensor and the thermometer will both be placed in a water bath or calibration chamber. When using a water bath, uniform temperature throughout the liquid can be accomplished by using a magnetic stirrer. Three or more temperatures must be evaluated spaced across the range of the sensor. The first at room temperature (e.g., 25 degrees Celsius), the second at freezing point (e.g., 0 degrees Celsius), and a third higher temperature (e.g., 45 degrees Celsius). When using a water bath, the higher temperature would be produced using a heat pad. While performing the water bath calibration, the following three conditions must be met:

- the sensor and the thermometer must not touch each other or the wall of the container holding them.
- both the thermometer bulb and the sensor must be submerged completely into the liquid (ideally at the same water level), if in a liquid bath.
- the stirrer must operate continuously during the calibration to maintain uniform temperature.

After the calibration is performed and the results show the sensor meets calibration limits, it can be placed in the shelter. A comparison should then be made with air temperature to ensure that the blower is working correctly. Be sure that the thermometer is in a shaded area and approximately at the same height as the sensor. In addition, the thermometer bulb must not come into contact with the person holding the thermometer and it should be kept as far away from their body as possible. If the sensor does not compare to the thermometer or represent the actual air temperature, the comparison and/or calibration should be performed again (see Form 10).

4.4.2 Frequency

Calibrations must be performed at the start of sampling, and at least annually for SLAMS sites, semi-annually for NCORE and PAMS sites, and quarterly for PSD sites. In addition, calibrations must be performed if the sensor fails an audit or if the sensor is damaged and repaired.

4.4.3 Limits

The calibration limit for outdoor temperature is ±1.0 degrees Celsius for SLAMS sites, ±0.5 degrees Celsius for NCORE, PAMS, and PSD sites. If this limit is not met, the sensor will require maintenance and another calibration until the limit is met. The data collected under out-of-calibration conditions are invalid back to the previous audit or calibration, or if it can be determined by analyzing the data, when the unit malfunctioned.

4.5 Preventive Maintenance

Most preventative maintenance on thermometry systems concerns housings and shelters. Instrument shelters must be cleaned as often as local weather conditions require. The air passageways and screens in radiation shields, both aspirated and naturally ventilated, should be cleaned out at least once every month. The blower should be checked during each visit. For remote sites or where data collection is critical, the blower should be changed periodically as recommended by the manufacturer. Lubricate the aspirator system as required. The spare parts inventory should include a sensor and blower. The most common cause of component failure is lightning. Obviously a system damaged by lightning will require repairs and calibration. All preventive maintenance activities should be entered into a site logbook.

4.6 Audits

A temperature audit consists of repeating the calibration procedure without making any adjustments (see Section 4.4.1). The audit must provide enough information to determine the validity of the data.

4.6.1 Frequency

A temperature audit must be performed every year. Ideally an audit should be performed 6 months after a calibration. This will allow the sensors to be evaluated twice a year. If a problem does occur, the amount of data which would be affected will be limited.

In the case of micrometeorological sites, which often operate on a short term basis, annual audits may not be applicable. However, a final audit must be performed before the dissolution of the site to confirm the validity of the data for any given operational period.

4.6.2 Limits

All temperature audit limits are the same as the calibration limits. If the blower is not functioning, then the data are invalid.

5.0 Humidity

Humidity is a general term for the water vapor content of air. Other, more specific, terms for humidity include: absolute humidity, relative humidity, specific humidity, mixing ratio, and dew point (Huschke, 1959). This section discusses the measurements of relative humidity and dew point. Relative humidity (RH) is a dimensionless ratio of the actual vapor pressure of air to the saturation vapor pressure at a given dry-bulb temperature. Dew point is the temperature to which air must be cooled, at constant pressure and constant water vapor content, to be saturated with respect to liquid water. Frost point is the temperature below 0 degrees Celsius at which air is saturated with respect to ice. There are many ways to measure the water vapor content of the atmosphere. These can be classified in terms of six physical principles (Middleton and Spilhaus, 1953). Three principles are listed below with instruments used with each:

1. Reduction of temperature by evaporation - Psychrometer

2. Formation of dew or frost by artificial cooling - Cooled mirror surfaces

3. Diffusion of moisture through porous membranes - Diffusion hygrometers

5.1 Types of Sensors/Instrumentation

Psychrometry identifies a basic technique for deriving both relative humidity and dew point temperature from a pair of thermometers - a dry-bulb thermometer that measures the ambient temperature, and a wet-bulb thermometer. The reservoir of the wet-bulb thermometer is covered with a muslin wick. When the wick is moistened and the thermometer ventilated, the indicated temperature is related to the amount of evaporation cooling that can take place at the existing ambient temperature, water vapor partial pressure, and the atmospheric pressure. A psychrometer uses this principle to obtain relative humidity and dew point.

1. Psychrometers - The temperature sensors in a sling psychrometer are usually mercury or alcohol filled thermometers. The same is true of portable motor-operated psychrometers, but the psychrometric principle has been used with sensors made of thermocouples, wire-wound resistance thermometers, thermistors, and bi-metal thermometers. Relative humidity and dew point are easily determined by observing the wet-bulb depression, which is the difference between the dry-bulb and the wet-bulb temperatures and then referring to a psychrometric table or chart. One must be certain to use the chart values corresponding to the correct atmospheric pressure range of the location where the observation is taken. Computer programs are also available to calculate out the humidity values. These programs may offer better accuracy than look-up tables.

More measurements of atmospheric water vapor have probably been made with the sling psychrometer than by any other manual method. When properly used and read, the technique is reasonably accurate. The most common errors encountered using this method are from radiation, rapid changes in conditions during reading, and parallax. The Assmann psychrometer continuously aspirates the thermometers and protects them from radiation. This will allow time and accessibility for a careful reading to avoid parallax (keep the eye perpendicular to the meniscus for best results). For good accuracy, particularly where a variety of observers are taking measurements, an Assmann or equivalent type psychrometer is recommended. One should use the psychrometric tables with dew point values for the altitude (pressure) of the location where measurements are being made.

2. Electrical Hygrometers - The resistance and capacitance of thin hygroscopic films on electrical hygrometers are affected by the presence of moisture. Measurement circuits provide the instrument output with scaled voltages and readouts of atmospheric moisture content. Corresponding temperature measurement is included within the instruments to calculate the results expressed in variables other than actual moisture content. Electrical hygrometers are considerably less expensive than some other automated relative humidity measurement methods and are readily adaptable to portable, hand-held units suitable for temporary measurements and transfer standard use.

3. Cooled-Mirror Hygrometer - In the early 1960's, the technique of detecting the dew point on a cooled mirror surface evolved into a production-type unit. This unit was operated automatically and had an optical dew-sensing system that incorporated thermoelectric cooling (Francisco and Beaubien, 1963). Of four meteorological grade, thermoelectric, cooled-mirror dew point instruments investigated (Mazzarella, 1977), three operate in the range from -50 degrees to +50 degrees Celsius. Linear thermistors are used to measure the mirror temperature in three of the units; a platinum wire sensor is used in the other. All are designed with simultaneous linear output signals for T_{dp} (dew point temperature) and T

(ambient temperature). Two of the manufacturers make claims of NIST-traceability with stated dew point accuracies ranging from ±0.2 degrees to ±0.4 degrees Celsius and ambient temperature accuracies ranging from ±0.1 degrees to ±0.5 degrees Celsius. All incorporate some form of standardization that involves clearing the mirror by heating, either automatically or manually. Although complex in design and operation, this type of cooled-mirror hygrometer is considered to be a functional standard.

5.2 Sensor Characteristics

Although the psychrometer is considered the most practical and widely used instrument for measuring humidity, two major problems are associated with wet- and dry-bulb psychrometry involving the accuracy of the thermometers and the cumulative errors related to operating technique (Quinn, 1968). An accuracy of ±1 percent at 23 degrees Celsius and 50 percent RH requires thermometers with relative accuracy of ±0.1 degrees Celsius. The commonly used thermometers with 0.5 degree Celsius divisions introduce an uncertainty of ±5 percent RH. This assumes that the readings were taken at the maximum wet-bulb depression, a difficult task with a sling psychrometer.

Electrical hygrometers use capacitive and resistive sensors which respond better to relative humidity than to dew point. Specifications for both types of sensors are similar. Capacitive sensors are most linear at low humidity levels and can tolerate condensation, although calibration shifts can occur. Resistive sensors are most linear at high humidity levels and cannot tolerate condensation, although some have automatic protection from saturation conditions. Dew point impedance sensors use a slightly different element; they measure absolute rather than relative humidity. The sensors are covered by membranes that are readily porous to moisture, although the membranes thermally insulate the sensor, causing some lag time in measurement.

The optical chilled (cooled) mirror technique of measuring dew point is a fundamental measurement. No calibration is required for the fundamental dew generating process. The measurement is the temperature of the surface at which the dew forms, and as with any electrical temperature measurement system, calibration is required. A balancing of the optical system to correct for changing the dry mirror reflectance that might result from contamination follows the process of periodically heating the mirror to a temperature above the dew (or frost) point. In the better instruments, automatic balancing is programmable in terms of frequency and length of time. It can also be accomplished manually.

5.3 Sensor Housings and Shields

Psychrometers of all types should be acclimated to the environmental conditions in which the measurements are to be made. In most cases, psychrometers should be stored in a standard instrument shelter so that the mass of the thermometers, and especially the mass of the housing, adjusts to the temperature of the air. Psychrometers with a stored water supply, such as those on a tower, must be shielded from solar radiation.

Electrical hygrometers should be aspirated and shielded from solar radiation.

Manufacturers of optical cooled-mirror dew point and temperature monitoring equipment provide housings for the sensors. These housings include forced ventilation and shielding from solar radiation.

5.4 Data Requirements

Electrical hygrometers used for meteorological monitoring applications have time constants generally longer than air temperature systems. The usual data of interest are hourly average values. Data should be reported in terms of the condition measured, dew point temperature, relative humidity, or wet-bulb and dry-bulb temperature. Computer programs may be used to convert among these if all the relevant variables are known. The station elevation may be used to estimate a nominal pressure if a measurement is not available. The temperature needed to convert a relative humidity measurement to dew point temperature is the temperature at the relative humidity sensor surface. This may not be the same temperature as that measured at some other location. On the other hand, the dew point temperature is a fundamental measure of the amount of water vapor in the air and is independent of air temperature. Relative humidity calculations can therefore be made given the dew point temperature and any temperature measurement point in the same general air mass.

Psychrometers are convenient devices for making spot checks on the performance of other devices, especially those that are permanently installed, providing the check is done under reasonably steady overcast conditions. The psychrometric technique built into tower installations presents servicing problems, especially at temperature extremes. High temperatures cause rapid evaporation. Low enough temperatures cause freezing.

Both the dew cell and the cooled-mirror type instruments are useful for 10-meter or taller tower pollution studies. For these installations, the sensors must be housed in the recommended shields with little, if any, aspiration for the dew cell and the recommended rate of aspiration for the cooled-mirror design.

5.5 Procurement

Sling psychrometers and aspirated psychrometers with thermometers shorter than 10 inches do not have sufficient resolution to provide the accuracy required checking other instruments. Equally important, the thermometers should have etched stems; i.e., the scale markings should be etched on the glass. Reliable thermometers are factory calibrated at a minimum of two temperatures, and usually at three. Thermometers calibrated with NIST-traceable standards are required.

Optical cooled-mirror dew point systems are now available commercially from several manufacturers, all whom currently incorporate either linear thermistors or platinum resistance temperature devices.

5.6 Calibration

Prior to any calibration adjustments, the operational period must be verified.

1. Dew Point - Calibration of dew point sensors consists of using a psychrometer with sufficient resolution to eliminate errors. The psychrometer could be a sling, motorized type, or an electronic sensor. If applicable, the thermometers need to be certified prior to use and every year thereafter against an NIST-traceable thermometer. If a sensor is used, it must be certified every year with the appropriate NIST standard (see Chapter 6, QA Manual). Temperature readings must be as accurate as possible. Care must be taken to make sure a stable reading is obtained for the wet-bulb temperature. In addition, the calibration needs to be performed in a shaded area or a place where no sunlight hits the thermometers/sensor and as close to the dew point sensor as possible. It is advisable to obtain several dew point measurements in as small a time period as possible and to take the sensor reading as close to the calibration reading as possible. This will help improve the precision and accuracy of the values. The dew point values must be obtained from the appropriate table/chart or by using a computer program.

2. Relative Humidity - The procedure for performing a calibration on relative humidity sensors is the same as the dew point calibration (see Form 13).

5.6.1 Frequency

Calibrations must be performed at least annually for SLAMS sites, semi-annually for NCORE and PAMS sites, and quarterly for PSD sites. In addition, calibrations must be performed if the sensor fails an audit or if the sensor is damaged and repaired.

Calibration of micrometeorological humidity sensors should be performed at the initial startup sampling. Should a micrometeorological site be put into operation on a permanent basis, humidity sensor calibrations must be performed annually with preventive maintenance performed in accordance with Section 5.7. However, micrometeorological sites often operate on a short-term basis. Therefore, annual calibrations may not be applicable. For short-term monitoring applications, an audit must be performed prior to the dissolution of the site to confirm the validity of the data for any given operational period.

5.6.2 Limits

Calibration limits for dew point are ±1.5 degrees Celsius dew point for PSD sites. No calibration criteria currently exists for dew point at SLAMS or NCORE sites. Calibration limits for relative humidity are ±7%RH at PSD and NCORE sites and ±10%RH at SLAMS sites. If these limits are not met, the sensor will require maintenance and another calibration until this limit is met. The data collected from a sensor that is out-of-calibration are invalid back to the previous audit or calibration, or if it can be determined by analyzing the data when the unit malfunctioned.

5.7 Field Operation and Preventive Maintenance

Field calibration checks should be made at least monthly on dew cell type units. The use of gold wire windings around the LiCl cylinder minimizes corrosion problems in polluted atmospheres. Periodic removal and flushing of old lithium chloride, followed by recharging with a fresh solution, improves data reliability. Once a mercury or alcohol liquid-in-glass thermometer is calibrated, there is no need for recalibration, unless it is to be used for reference or as a transfer standard. Errors in wet-bulb temperatures are most frequently the result of an improperly installed or dirty muslin wick, the repeated use of tap water instead of distilled water, or human error in reading. Wicking material used on psychrometers must be washed to remove traces of sizing and fingerprints. Once cleaned, the material is tied at the top of the thermometer bulb and a loop of thread placed around the bottom so the thermometer bulb is tightly covered. To prevent solid materials from collecting on the cloth and prevent proper evaporation, the wick should be wetted with distilled water. Slinging or motor aspiration should be done in the shade, away from reflected or scattered radiation, at a ventilation rate of about 3 to 5 m/s. Many technique-related errors are minimized by using an Assmann-type, motor-operated psychrometer providing the instrument is allowed to assume near ambient conditions prior to use.

The cooled-mirror instruments require no calibration except for the minor temperature sensor. Depending on environmental conditions, the mirror is easily cleaned with a cotton tipped swab dipped in the recommended cleaning fluid, usually a liquid with an alcohol base. While the accuracy of a psychrometer is inferior to that of the optical chilled mirror system, an occasional check at the intake to the sensor shield is recommended under the provisions specified earlier. All operational and preventive maintenance activities should be entered in a logbook.

5.8 Audits

1. Dew Point - A dew point audit consists of repeating the calibration procedure (See Form 14).

2. Relative Humidity - A relative humidity audit consists of repeating the calibration procedure (see Form 15).

5.8.1 Frequency

Dew point and relative humidity audits must be performed semi-annually at PSD and PAMS sites, annually at SLAMS and NCORE sites. Ideally audits should be performed 6 months after a calibration. This will allow the sensors to be evaluated twice a year. If a problem exists, the amount of affected data will be limited.

Should a micrometeorological site be put into operation on a permanent basis, humidity sensor audits must be performed annually with preventive maintenance performed in accordance with Section 5.7. However, micrometeorological sites often operate on a short-term basis. Therefore, annual audits may not be applicable. In that circumstance, an audit must be performed before dissolution of the site to confirm the validity of the data for any given operational period.

5.8.2 Limits

All dew point and relative humidity audit limits are the same as the calibration limits (See Section 5.6.2).

6.0 Radiation

Solar energy is the driving force of large-scale atmospheric motion. Although air pollution investigators normally consider the measurement of radiation secondary in importance to wind and temperature measurements, radiation is directly related to atmospheric stability. It is measured as total incoming global radiation, as outgoing reflected and terrestrial radiation, and as net total radiation.

Quantitatively, solar radiation is described in units of energy flux, either Watts/m^2, or calories/cm^2/min. At IDEM/AMB, the unit of measure used for UV radiation is millicalories/cm^2/min. The unit of measure used for solar radiation is Langleys/min.

Conversions are as follows:

1 cal/cm^2/min = 697.3 Watts/m^2
1 cal/cm^2 = 1 Langley (Ly)
1 Ly = 11.6 Watt hours/m^2

When measured in narrow wavelength bands, solar radiation may be used to evaluate such air pollution indicators as turbidity, amount of precipitation (water), and rates of photochemical reactions. This chapter will cover only broadband measurements and sunshine.
The generic term “radiometer” refers to any instrument that measures radiation, regardless of wavelength. Shortwave radiation has wavelengths less than 4 micrometers (μm) and is subdivided as follows:

Ultraviolet (UV)	0.20 μm to 0.38 μm
Visible	0.38 μm to 0.75 μm
Near-infrared	0.75 μm to 4.00 μm

The infrared (IR) radiation band from 4 μm to 100 μm is considered long wave radiation. The instruments most commonly used for environmental monitoring are discussed below.

6.1 Types of Sensors/Instrumentation

1. Pyranometers - These instruments measure the solar radiation received from the sky, including the total sun and sky shortwave radiation. Most pyranometers incorporate a thermopile as a sensor. Others that measure a narrower, shortwave bandwidth use a silicon photovoltaic cell as a sensor. The spectral pyranometer with two hemispherical domes is designed to measure sun and sky radiation totally, or in defined colored Schott glass filter domes for the clear glass outer dome.

2. Bimetallic Recording Pyranometers - Robitzsch of Germany designed bimetallic recording pyranometers, also known as actinometers. These mechanical sensors consist of two or three bimetallic strips, alternately painted black and white, that respectively absorb and reflect solar radiation. The resulting differential heating produces a deformation that is transmitted mechanically through levers and a pen arm to a clock-wound drum recorder. Although of limited accuracy, these instruments are useful for locations with no commercial power.

3. Net Radiometers – Also known as net pyradiometers, these are designed to measure the difference between downward and upward total radiation, including the total incoming and outgoing short wave and long wave radiation. There are two basic types of net radiometers. The ventilated plate type, often referred to by the name of the designers (Gier and Dunkle), is more popular for research applications than the type with hemispherical polyethylene domes originally designed by Funk. Both incorporate thermopiles with blackened surfaces. Because net radiometers produce a signal with a positive sign when the incoming radiation exceeds the outgoing, the recorder equipment must be designed with an offset zero.

4. Sunshine Recorders - Sunshine recorders are designed to provide information on the hourly or daily duration of sunshine. One type of sunshine recorder available is the Campbell-Stokes design designated as the interim reference sunshine recorder "IRSR" by the World Meteorological Organization (WMO). The device consists of a glass sphere 10 cm in diameter mounted in a spherical bowl. The sun's rays are focused on a card that absorbs radiation and changes color in the presence of sunlight. The recorder is used infrequently in the United States but extensively abroad, primarily for the collection of climatological data. The National Weather Service routinely uses a Sunshine Switch, which incorporates one shaded and one exposed photocell.

6.2 Instrument Characteristics

Only the characteristics of pyranometers and net radiometers, the two types of instruments used most frequently in pollution-related programs, will be discussed in detail in this section.

1. Pyranometers - The pyranometer is not to be confused with the pyrheliometer, "an instrument for the measuring the intensity of direct solar radiation at normal incidence" (WMO, 1971). The pyrheliometer is mounted in a solar tracker, or equatorial mount, automatically pointing to the sun as it traverses from east to west. By contrast, the pyranometer is mounted facing toward the zenith. Ideally, the response of the thermopile sensor in the pyranometer is proportional to the cosine of the angle of the solar beam, and is constant at all azimuth angles. This characteristic is known as the Lambert Cosine Response, an important characteristic of pyranometers. For the majority of applications related to atmospheric pollution, Class 2 and Class 3 are satisfactory (see Table 1).

2. Net Radiometers - Most net radiometers now available commercially are made with a small disc shaped thermopile covered by polyethylene hemispheres. In most units, the material used for shielding the element from the wind and weather is very thin and is transparent to

wavelengths of 0.3 to 60 μm. Until recently, the internal ventilation and positive pressure required to maintain the hemispheres of net radiometers in their proper shade was considered critical; however, new designs have eliminated this problem. The plate-type net radiometer, most often the modified Gier and Dunkle design sold commercially in the United States, is occasionally used in routine air pollution investigations. The thermopile heat flow transducer is blackened with a material that is easily cleaned with water or naphtha. Because the thermopile is uncovered for total spectrum response, a built-in blower, available for operation on 115 V 50/60 Hz or 12 V DC, draws air across the element at a constant rate eliminating the effects of varying natural winds. The device is temperature-compensated and typically has a sensitivity of 2.2 μV per W/m^2, a response time of 10 seconds, and a relative accuracy of two percent in calibration. When supplied with a reflective shield on its lower surface, this plate type net radiometer of the Gier and Dunkle design becomes a total hemispherical or unshielded pyranometer.

6.3 Recorders and Integrators for Pyranometers and Net Radiometers

The relatively high impedance and low signal of thermopile sensors, excluding silicon photovoltaic cells, limits their use with both indicating meters and recording meters. Electronic millivolt potentiometer recorders incorporating variable-range rheostats are preferred. The variable-range rheostat permits the exact matching scale to interchangeable sensors so that deflections of the meter represent engineering units, e.g., W/m^2 or $cal/cm^2/min$. The alternative is a standard voltmeter potentiometer recorder where the data, in millivolts, must be translated to units of energy, corresponding to full-scale values of 1370 W/m^2 or 1.96 $cal/cm^2/min$. With some sensors, it is necessary to use a preamplifier to increase the level of the signal. It may also be necessary, especially if the signal is to be used as an input to a computer, to combine pre-amplification with scaling.

6.4 Procurement

Many types of radiation instruments are available for environmental considerations, meteorological research, and solar energy. Except for special studies, the requirements for relating radiation to stability can be satisfied by purchasing sensors of Class 2 or Class 3 as identified by the World Meteorological Organization (WMO) (see Table 1). Class 2 sensors offer the advantage of providing data comparable to that at National Weather Service stations and at key monitoring locations of Department of Energy (DOE). The sensors to be specified should be commercially available, field proven by the manufacturer for several years, and have the technical requirements established by WMO standards. An American Society for Testing and Materials (ASTM) standard is now under consideration. When purchasing a recorder or integrator, one must match the calibration factor or sensitivity of the sensor to the readout equipment. It must be recognized that the signals from net radiometers, in contrast to pyranometers, require zero-offset capability to accommodate both negative and positive voltage outputs.

6.5 Calibration

Prior to any calibration adjustments, the operational period must be verified.

The user of a pyranometer or net radiometer is normally not able to calibrate the sensor. The best the user can do is to perform field calibration checks. These checks involve a side-by-side comparison of the field sensor to a laboratory sensor of similar design, the calibration of which can be traced to an NIST-traceable standard (see Item 2 of this section and Form 16). However, all sensors should be returned to the manufacturer or to a laboratory with the facilities to check the calibration.

6.5.1 Radiation Sensors

The person performing the calibration check will use a transfer standard sensor of the same type as the field sensor. The transfer standard used to perform the check should still have a valid calibration. The operator must set the transfer standard at the same height as the sensor and must make sure no light is obstructed for either of the sensors. In addition, both the sensor and the transfer standard must be leveled. The calibration check should be performed on a clear day. If ideal weather conditions do not exist, the comparison can still be made, but the percent error may not be representative since the values collected will be at such a minimal level. Readings must be taken at the same time to obtain an accurate comparison. For best results, compare the two sensors over several hours or even days. Have both sensors hooked up to the same recorder, and obtain hourly readings from both sensors. Besides hourly comparisons, the average percent error for the whole sampling period can be calculated.

6.5.2 Recorder or Integrator

Calibrating the recorder or integrator is an easy task. The standard method involves the use of a precision potentiometer to input known voltages into the circuit. Introducing a series of voltages covering the full scale (checking first up-scale and then downscale) can check the linearity of the readout instrument. Adjustments should be made as necessary. In the absence of a precision potentiometer, it may be possible to introduce a calibrated millivolt source that covers one or two points. Integrators can be checked the same way, except the input value must also be timed.

6.5.3 Frequency

Net radiometers are delicate instruments and require more frequent attention than pyranometers.

Ideally an audit should be performed 6 months after a calibration check or factory calibration, and at the dissolution of a site. This will allow the sensors to be checked twice a year. If a problem does occur, the amount of data which would be affected will be limited.

Micrometeorological - Since these sites are often temporary, yearly audits may not be applicable. However, at the dissolution of a site, an audit should be performed on the sensors. If radiation sensors should be put into operation on a permanent or long term basis, an audit must be performed annually.

6.5.4 Limits

The limit for a calibration check is ±5.0%. The 5% limit should be based on the full comparison and when values are elevated. Even if an hour is more than 5%, if the tracking of the two units is comparable then data should be considered valid. An in-depth analysis is always needed for radiation data. The calibration should be performed under clear skies and over several days. Data collected under out-of-calibration conditions are invalid.

6.6 Preventive Maintenance

All types of radiometers require frequent cleaning to remove any material deposited on the surface that will intercept the radiation. In most cases, this is a daily operation. The outer hemisphere should be wiped clean and dried with a lint-free soft cloth. Any scratching of the surface will alter the transmission properties of the glass, so cleaning must be done with care. If snow, glazed ice, hoarfrost, or rime ice is present, an attempt should be made to remove the deposit carefully with warmed cloths.

Should the internal surface of a pyranometer's outer hemisphere become coated with moisture, it can be cleaned by carefully removing the outer hemisphere on a dry day and allowing the air to evaporate the moisture. If removal of a hemisphere exposes the thermopile element, extreme care should be taken because it is fragile and easily damaged. About once each month, the desiccant installed in most pyranometers should be inspected. Whenever the indicating silica gel drying agent is pink or white instead of blue, it should be replaced or rejuvenated by drying it on a pan in an oven at 135 degrees Celsius. The level should be checked after each servicing of the radiometer, or at least monthly. Significant errors can result from misalignment.
Net radiometers require more frequent maintenance attention than pyranometers. It is necessary to replace the polyethylene domes as often as twice a year or more before the domes become discolored, distorted, or cracked. More frequent replacement is necessary in polluted environments due to accelerated degradation of plastic hemispheres when exposed to pollutants. All preventive maintenance activities should be recorded in a site logbook.

6.7 Radiation Audits

The audit consists of repeating the calibration check (see Form 17).

6.7.1 Frequency

Ideally an audit should be performed 6 months after a calibration check or factory calibration, and at the dissolution of a site. This will allow the sensors to be checked twice a year. If a problem does occur, the amount of data which would be affected will be limited.

Micrometeorological - Since these sites are often temporary, yearly audits may not be applicable. However, at the dissolution of a site, an audit should be performed on the sensors. If radiation sensors should be put into operation on a permanent or long term basis, an audit must be performed annually.

6.7.2 Limits

All audit limits are the same as the calibration limits (see Section 6.5).

7.0 Precipitation Measurements

In any method of precipitation measurement, the aim should be to obtain a sample that is representative of the rainfall in the area. At the outset, it should be recognized that the extrapolation of precipitation amounts from a single location to represent an entire region is an assumption that is statistically questionable. A network of stations with a density suitable to the investigation is preferable. Two basic types of precipitation collectors are non-recording and recording.

7.1 Types of Sensors/Instrumentation

1. Non-recording Gages - In its simplest form, a precipitation gage consists of a cylinder, such as a can with straight sides, closed at one end and open at the other. The depth of the liquid in the gage may be measured with a measuring stick calibrated in subdivisions of centimeters or inches.

To obtain greater resolution, as in the case of the standard 8-inch gage made to National Weather Service Specification No. 450.2301, the gage is constructed with a ratio of 10:1 between the area of the outside collector cylinder and the inside measuring tube. The funnel attached to the collector directs the precipitation into the tube and minimizes evaporation loss. Amounts in excess of two inches of rainfall overflow into the outer can, and all measurements of liquid and melted precipitation are made in the measuring tube with a measuring stick. The automatic wet/dry precipitation collector, available in several designs, represents a specialized, non-recording instrument designed for programs involving the chemical and/or radioactive analysis of precipitation. The collector is built with a sensor that detects the onset and cessation of precipitation and automatically releases a lid to open and cover the collector. In one design, the lid can remain open during either wet or dry periods. Another model is made with two collectors; the lid is made to cover one bucket during periods of rain and snow. In equipment of this kind involving precipitation chemistry, the volume of water in proportion to the constituents collected with the water is important, so evaporation must be kept to a minimum.

2. Recording Gages - Recording gages are of two basic designs based on their operating principles; the weighing-type gage and the tipping bucket-type gage. The former, when made to National Weather Service Specification No. 450.2201, is known as the Universal gage, indicating usage for both liquid and frozen precipitation. There are options for the remote transmission of signals from this type of gage. The standard National Weather

Service Tipping Bucket Rain Gage is designed with a 12-inch collector funnel that directs the precipitation to a small outlet directly over two equal compartments, or buckets, which tilt in sequence with each 0.01 inches of rainfall. The motion of the buckets causes a mercury switch closure. Normally operated on 6 V DC, the contact closure can be monitored on a visual counter and/or one of several recorders. The digital-type impulse can also be used with computer-compatible equipment.

7.2 Instrument Characteristics

The most accurate precipitation gage is the indicating-type gage; however, the recording-type gage measures the time of beginning and ending of rainfall and the rate of fall. The Universal weighing gage incorporates a chart drum that is made to rotate by either an 8-day spring-wound clock or a battery-powered clock. Recent developments include a unit with a quartz crystal mechanism with gear shafts for a wide range of rotation periods from half a day to one month.

1. Weighing Gage - The weighing gage is sometimes identified by the name of its designer (Fergusson) and comes with one of two recording mechanisms. In the single traverse unit, the pen moves from the base of the drum to the top, typically a water equivalent of 6 inches. In a dual traverse unit, the pen moves up and down for a total of 12 inches of precipitation. A variation of the weighing gage, a "high-capacity" design with dual traverse, will collect as much as 760 mm or 30 inches. To minimize the oscillations incurred by strong winds on the balance mechanism, weighing gages are fitted with a damper immersed in silicone fluid. By incorporating a potentiometer in the mechanism, the gage becomes a remote-transmitting unit, capable of providing a resistance, or as another refinement, a voltage proportional to the amount of precipitation collected. Linearity of response is usually a factory adjustment involving the use of calibrated weights to simulate precipitation amounts. In spite of the manufacturer's specifications, it is doubtful that the gage can resolve 0.01 inches, especially when the bucket is nearly empty.

2. Tipping Bucket Gage - In the tipping bucket gage, the balance of the buckets and leveling of the bucket frame are critical. Low voltage at the gage is imperative for reasons of safety. Power is typically 6 V DC. The signal is provided by a switch closure every time the bucket assembly tips (0.01 inches rainfall per bucket). An event recorder calculates rain rates with pens energized sequentially to improve resolution. The tipping bucket (a mechanical device) takes time to go from one position to the next. When the rate of fall is high, there is spillage and the unmeasured precipitation falls into the reservoir. Where there is a need for greater accuracy, the collected water is measured manually, and excess amounts are allocated proportionately in the record. The accuracy of the gage is given as 1% for rainfall rates of 1 in/hr. or less; 4% for rates of 3 in/hr.; and 6% for rates up to 6 in/hr.

3. Windshields and Heaters - Accuracy of measurement for all types of gages is influenced more by exposure than by variation in design. Windshields represent an essential accessory to improve the catch of precipitation, especially snow in windy conditions. The improved Alter design, made of 32 free-swinging but separated leaves supported 1/2 inch above the level of the gage collecting orifice, is an effective way to improve the catch. In a comparison

of shielded and unshielded 8-inch gages, it has been shown that at a wind speed of 5 mph, the efficiency of the unshielded gage decreases by 25 percent, and at 10 mph, the efficiency of the gage decreases by 40 percent (Weiss, 1961).

In below freezing conditions, when the catch in a gage is snow or some other form of solid precipitation, it is necessary to remove the collector/funnel of non-recording gages and the funnel in recording gages. Some instruments are available with built-in heater elements that are thermostatically controlled. An effective heater for conditions that are not too severe is an incandescent lamp installed in the housing of the gage. Caution should be exercised; too great a heat will result in evaporative loss.

7.3 Precipitation Data Requirements

In research studies, especially those related to acid rain, the instrument used most frequently is the Automatic Precipitation Collector with one or two collecting buckets and a cover to prevent evaporation. In operational activities, the choice is between the weighing gage and the tipping bucket gage. For climatological surveys, the choice might include one of the above gages as well as a non-recording type gage. The use of a windshield is recommended to minimize the errors that result from windy conditions if the application requires maximum accuracy.

The precipitation measurement made in air quality monitoring stations is frequently used for descriptive purposes or for episodic analysis. If the effort required to achieve the level of accuracy specified by most manufacturers of electrical recording gages is more than the application of the data can justify, a tolerance of 10 percent may be adequate.

7.4 Procurement

A variety of gages are available commercially. In general, gages which conform to the standards established by the National Weather Service result in the fewest problems. For example, there are numerous 8-inch gages available, but those following NWS specifications are made only of brass and copper, are more durable, and are reported to rupture less frequently under extended freezing conditions than those made of galvanized steel.

The procurement of a weighing-type gage should include a tripod mounting base as well as a set of calibration weights. For locations that may not be readily accessible, or locations with heavy precipitation, the bucket of the weighing gage should have an overflow tube. If the resolution of time is not too important, recording rain gages of the drum type can be obtained with monthly rather than weekly mechanisms. Unless the tipping bucket gage is equipped with a heater, it is of no use for frozen precipitation.

7.5 Calibration

Prior to any calibration adjustments, the operational period must be verified.

1. Precipitation Gages - Bench calibrations for gages should follow the recommendation of the manufacturer. The electrical output gage or the drum recording gage measures weight, whether total weight in the case of the "weighing gage" or increments of weight in the case of the tipping bucket gage. Density of water is assumed so the weight can be expressed in units of volume or depth assuming the area of the collector opening. Calibrations of the measurement apparatus can be based upon the introduction of known volumes of water. For rate-sensitive systems such as the tipping bucket, the rate of simulated precipitation should be kept less than one inch per hour.

Calibrations require properly leveled weighing systems (gages) whether on the bench or in the field. Once the precipitation gage is installed in the field, a final calibration check should be made prior to any sampling. For the weighing bucket, standard weights or a suitable substitute can be used to perform the calibration check. To check the operation of the tipping bucket, the best approach is to put a known quantity of water in a can with a small hole so that the slow flow can be timed. It may be necessary to adjust the set-screws, which act as limits to the travel of the tilting buckets. The average of a minimum of ten tips should be used. Three different amounts of water should be used for the calibration.

7.5.1 Frequency

Calibration of precipitation gages must be performed at least annually at SLAMS sites, semi-annually at NCORE and PAMS sites, and quarterly at PSD sites. In addition, calibrations must be performed if the sensor fails an audit or the sensor is damaged and repaired.

Calibration of micrometeorological precipitation gages should be performed at the initial start-up sampling. Should a micrometeorological site be put into operation on a permanent or long term basis, precipitation gage calibrations must be performed annually with preventive maintenance performed in accordance with Section 7.6. However, these sites often operate on a short term basis. Therefore, annual calibrations may not be applicable. In that circumstance, an audit must be performed prior to the dissolution of the site to confirm the validity of the data for any given operational period. In addition, calibrations must be performed if the unit fails an audit or is damaged and repaired.

7.5.2 Limits

The calibration limit for precipitation gages is ±10.0%. If this limit is not met, the sensor will require maintenance and another calibration until the limit is met. Data collected under out-of-calibration conditions are invalid.

7.6 Preventive Maintenance

Possible leaks in the measuring tube or the overflow container of a precipitation gage are easily checked. The receptacles are partially filled with water colored with red ink and placed over a piece of newspaper. This procedure is especially applicable to the clear plastic 4-inch gage,

which is more easily damaged. Repairs are performed by soldering the 8-inch gage and by applying a solvent to the plastic.
A number of pens, some with greater capacity than others, can be used with the universal gage. All require occasional cleaning, including a good soaking and wiping in a mixture of water and detergent. Another source of trouble is the chart drive, but these problems can sometimes be avoided by having the clock drive lubricated for the environmental conditions expected. It is a good practice to have spare clocks in stock.

Routine visual checks of the performance of weighing type gages should be made every time there is a chart change. The time, date of change, and site location should be documented. Routine maintenance should include inking the pen and winding the clock. Battery-powered chart drives will require periodic replacement of batteries based on either experience or manufacturer's recommendations. All preventive maintenance activities should be put into a site logbook.

7.7 Audits

Audits on precipitation gages consist of challenging the gage with amounts of water known to at least a one percent accuracy of the total to be used. This method will provide an accuracy of the measurement system, but not the collection efficiency of the gage in natural precipitation. For tipping bucket gages, use an amount of water at a rate which will not overflow the tipping bucket. The number of tips performed in the audit may depend on the type of sensor. The manufacturer's manual should be used as a guide to determine the amount of water used in the audit. For weighing gages, it is more convenient to use calibration weights to challenge the weighing mechanism rather than using the gallons of water necessary for full scale testing (See Form 18).

7.7.1 Frequency

Precipitation sensors should be audited every year. Ideally an audit should be performed 6 months after the calibration check. This will allow the sensor to be challenged twice a year.

Should a micrometeorological site equipped with precipitation gages be put into operation on a permanent or long term basis, an audit must be performed every year. Ideally an audit should be performed 6 months after a calibration check. This will allow the sensors to be checked twice a year. If a problem does occur, the amount of data that would be affected will be limited.

Lastly, an audit must be performed prior to the dissolution of the site to confirm the validity of the data for any given operational period.

7.7.2 Limits

All audit limits are the same as the calibration limits.

8.0 Atmospheric Pressure

Surface atmospheric pressure is generally not a required measurement for an air pollution meteorology application. Atmospheric pressure can provide useful information in evaluating data trends, as well as for determining flows in particulate samplers.

8.1 Types of Instruments

1. Mercury Barometer - The mercury barometer measures the height of a column of mercury that is supported by the atmospheric pressure. It is a standard instrument for many climatological observation stations, but it does not afford automated data recording. Readings must be corrected for temperature and gravity to obtain station pressure. Station pressure is the atmospheric pressure at that location and not corrected for sea level.

2. Aneroid Barometer - The aneroid barometer consists of two circular disks bounding an evacuated volume. The disks flex as the pressure changes changing their relative spacing, which is sensed by a mechanical or electrical element and transmitted to a transducer. A barograph is usually an aneroid barometer whose transducer is a mechanical linkage between the bellows assembly and an ink pen providing a trace on a rotating drum. A more sophisticated aneroid barometer providing a digital output has been developed, consisting of a ceramic plate substrate sealed between two diaphragms. Metal-coated areas on the ceramic substrate form one plate of a capacitor, with the other plate formed by the two diaphragms. The capacitance between the internal electrode and the diaphragms increases linearly with applied pressure. The output from this barometer is an electronic signal that can be processed and stored digitally.

8.2 Calibration

Prior to any calibration adjustments, the operational period must be verified.
The calibration of atmospheric pressure sensors can be performed using an aneroid barometer that has been certified with the primary standard mercury barometer at station pressure. However, an electronic barometer will provide the user with better accuracy (see Form 19).

8.2.1 Frequency

Atmospheric pressure calibrations must be performed every year. In addition, calibrations must be performed if the sensor fails an audit or if the sensor is damaged and repaired.

8.2.2 Limits

The calibration limit for atmospheric pressure is ±2.25 mmHg (±3.0 millibars). The data collected under out-of-calibration conditions are invalid.

8.3 Audits

The procedure for audits on atmospheric pressure sensors is the same as performing a calibration (See Form 20).

8.3.1 Frequency

An atmospheric pressure audit must be performed every year. Ideally the audit should be performed 6 months after a calibration. This will allow the sensors to be evaluated twice a year. If a problem occurs, the amount of data that would be affected will be limited.

Micrometeorological - Should a site equipped with atmospheric pressure sensors be put into operation on a permanent or long term basis, an audit must be performed every year. Ideally an audit should be performed 6 months after a calibration check. This will allow the sensors to be checked twice a year. If a problem does occur, the amount of data that would be affected will be limited.

Lastly, an audit must be performed prior to the dissolution of the site to confirm the validity of the data for any given operational period.

9.0 Data Validation/Screening

Once the data are collected, it should be reviewed to screen for incorrect data values. The data will be audited by the agency's or company's Quality Assurance chief (see Chapter 12 of this manual for procedures) prior to entry into AQS.

Micrometeorological - Regardless of the end purpose for micrometeorological data collection and irrespective of the parameter(s) sampled, all data should be reviewed following the guidelines set forth in Chapter 12 of this manual.

10.0 Quality Assurance Program

A formal quality assurance program should be designed into the monitoring system so that provisions may be made in the system design for desired quality control checks and for better monitoring of system operations. If these activities are planned and provided for by incorporation of necessary readouts, calibration sources, etc., then they are more likely to be performed in a satisfactory manner. The quality assurance activities necessary for a monitoring program are determined by the program data quality requirements, which are determined by the purpose for which the data are to be used. Considerations must also be given to possible future applications of the data. The formal plans for quality assurance must be presented in a document: the QA Plan. This document lists all necessary quality-related procedures and the frequency with which they should be performed. Specific information includes the following:

1. Project personnel responsibilities - Responsibilities of personnel performing tasks that affect data quality.

2. Data reporting procedures - Brief description of how the data are produced, delineating functions performed during each step of the data processing sequence.

3. Data validation procedures - Detailed listing of criteria to be applied to data for testing its validity, how the validation process is to be carried out, and the treatment of data found to be questionable or invalid.

4. Audit procedures - Detailed description of what audits are to be performed, and an audit procedure (referencing document procedures whenever possible). Also, description of internal and external systems audits including site inspections of supervisory personnel or others.

5. Calibration procedures - Detailed description of calibration techniques and frequency for each of the sensors or instruments being used. Both full calibrations and zero and span checks should be defined.

6. Preventive maintenance schedule - Detailed listing of specific preventive maintenance functions and the frequency at which they should be performed. This includes not only routine equipment inspection and wearable parts replacement, but also functional tests to be performed on equipment.

7. Quality reports - Schedule and content of reports for submission to management describing status of quality assurance program.

More details on the requirements for a QA Plan that is to be submitted to USEPA are available online at www.epa.gov/quality1/qapps.html.

The quality assurance program includes the implementation of all functions specified in the QA Plan. This implementation of these functions involves personnel at all levels of the organization. Technicians who operate equipment must perform preventive maintenance and quality control checks on the measurement systems for which they are responsible. They must perform calibrations and, when required, participate in internal audits of stations operated by other technicians. Their immediate supervisors should ensure all specified QA tasks are performed, and should review logs and control charts to ensure that potential problems are corrected before significant data loss occurs.

The overall QA program lies with the person responsible for quality assurance. The responsibility includes the assessment of the quality of the data acquired, the preparation of QA status reports, and management of the quality assurance effort in a cost-effective manner. The quality assurance coordinator must track the implementation and effectiveness of the QA plan through reports from subordinates, personal communications, on-site inspections, and review of audit data. Data validation procedures also provide indications of degradations of data quality; however, these indications are not produced until data problems occur and data are lost. It is more cost effective, considering the value of the data, to implement adequate assessment and preventive measures to correct data quality problems before significant quantities of data are lost.

10.1 Micrometeorological Monitoring Applications

A formal quality assurance program should be designed into any monitoring system so that provisions may be made in the system design for desired quality control checks and for better monitoring of system operations. However, the very nature of a micrometeorological site makes quality assurance of the utmost importance. It has been mentioned numerous times throughout the text of this chapter, that micrometeorological sites by their very nature, often fall outside normal siting and sampling criteria; so strict adhesion to established QA protocol may not be possible. Therefore, it is essential to carefully evaluate and consider the ramifications of a less than ideal site location upon the resultant data gathered there.

10.2 Performance and Systems Audits

Performance and systems audits provide the manager with the best information for quantitative and qualitative assessment of the status of the QA program, and are the most unbiased measures of data quality available to the QA coordinator.

10.2.1 Systems Audit

The systems audit is an inspection of the monitoring stations for indications of proper quality control procedures and adequacy of the instrumentation for making the desired measurement. Inspections are made to determine the following:

- Adequacy of record keeping
- Level of preventive maintenance
- Suitability of equipment used for calibration and operational checks
- Adequacy of operating procedures

Systems audits should be performed at the beginning of a monitoring program shortly before data acquisition has begun and yearly thereafter. If data quality does not meet the requirements of the program, a systems audit should be performed more frequently.

An impartial group completely independent of the group operating the monitoring program should perform systems audits. This is especially important if the audits are to be used to establish credibility for the measurement being taken (e.g., for demonstrating data quality to the agency requiring the measurements or for possible use in a court of law). If the systems audit is simply to function as an on-site inspection as part of the management review process, then the supervisor or manager responsible for the station operation may perform it.

10.2.2 Performance Audits for non-Automated Systems

Performance audits provide a quantitative indication of the accuracy of measurements being made by the physical verification of the instrument calibration. Suggested audit methods were mentioned earlier in this chapter. Independent investigators should execute the performance audits.

10.2.3 Performance Audits for Automated Systems

Leading Environmental Analysis and Display System (LEADS) is an automated near real-time data acquisition system. See Chapter 1 of the Quality Assurance Manual for introductory LEADS information.

10.2.4 Interpretation of Audit Results

The interpretation of audit results for meteorological instrumentation will be somewhat different from interpretation for ambient air monitoring instruments because of differences in the audit techniques. Air monitoring equipment is accessible because it is usually installed in air-conditioned shelters with the sample drawn into the instrument through a tube. Calibrations or audits are performed by generating known concentrations of the monitored gas in a manifold and letting the instrument draw its sample from that manifold in the same manner in which it would draw the ambient air sample. The test conditions, therefore, accurately simulate the measured conditions with the measured quantity being carefully controlled. Meteorological instrumentation; however, usually consists of a sensing element that must be located directly in the “field” being measured without altering the field. Once installed, the instrument may only be checked by generating an artificial field (e.g., spinning anemometer cups with a motor, orienting the wind vane toward aiming stakes, or submersion of a temperature sensor in a water bath). Checks made in this manner do not detect or quantify coupling errors that occur at the sensor/air interface (slippage of cups in wind because of increased bearing friction, errors in indicated direction due to geometrical asymmetry of the vane, or effects of radiation on temperature measurements). But to produce a “natural” field for meteorological parameters at the monitoring site would be very difficult, if not impossible. Therefore, these checks represent only a calibration of a portion of the system and may not be routinely used to evaluate accuracy on the entire measurement system.

The instrument may also be checked by the technique of collocated sensors, in which the audit sensor is subject to the same air/sensor interface errors as the audited sensor. When audits of this type are conducted, the ambient field as measured by the audit device is assumed to be the known field. Care must be taken when this method is used for calibration or audit purposes because the characteristics of the atmosphere are not controlled, and unknown spatial and temporal variations may exist.

The audit data indicate the state of instrument calibration because most audit procedures verify the total system except for the air/sensor interface. It is possible for a system to receive a good audit report and still make poor measurements of meteorological conditions due to problems at the air/sensor interface or poor siting. However, this is not likely if good sensors are used and proper siting precautions are taken. To further minimize the chances of inaccurate measurements going unnoticed, performance audits should always be accompanied by inspections for problems that might cause the measured values to be unrepresentative of ambient conditions.
The calibration errors indicated by a performance audit should fall within the limits specified in the QA Plan. Limits are mentioned earlier in this chapter. Any audit results falling outside these limits indicate a problem that should be rectified by normal maintenance procedures and

followed by another audit of the system. The audits are only checks and should not be used to determine calibration coefficients for the instrument or for other types of data correction or adjustment.

For meteorological measurement systems that are audited by the collocated instrument technique, two sets of data will result. These are the normal measured values and the data recorded from the audit system. If the monitoring system is properly calibrated and maintained, then the auditing system is susceptible to the same levels of errors as the monitoring system. To make a quantitative assessment of the audit data, two techniques are available; i.e., manual inspection and statistical evaluation.

A manual examination of audit vs. sample data for differences within acceptance limits may be performed. Either instantaneous values or average values over the period of audit may be compared. Also, if a collocated test was run over a sufficient period, and widely varying levels of the measured variable were encountered, then results of the regression between the audit and sample values will yield difference and bias information.
Statistical evaluation of audit results, either from audits performed on multiple stations or multiple audits on a single station may be performed. Simple tests, which detect bias in system measurements through audit data taken over a network, are described in the QA Handbook for Air Pollution Measurement Systems, Vol. 1, Appendix G (April, 1994), or online at

http://www.epa.gov/ttn/amtic/files/ambient/qaqc/r94-038a.pdf

These tests include the sign test and the paired t-test. More complex tests are available.

10.3 Quality Assurance Program Reports

Periodically, the quality assurance coordinator should prepare a report for management describing the status of the quality assurance effort. This report should provide quantitative information on the quality of data, activities performed to improve data quality, and the cost of the QA efforts.

Specifically, the report should cover the following:

1. Results of performance audits
2. Results of system audits
3. Percentage of data reported
4. Cost of QA effort
5. Problems that degraded data quality and corrective actions taken

No general format exists that will serve for all quality reports. The exact contents will depend on the level of QA activity for the group collecting the data and the extent of the monitoring network. It is important that the document be clear and concise. Voluminous, highly detailed information should be summarized or, if necessary, placed in a separate appendix. Reports that are complex and difficult to comprehend will not effectively communicate their message.

11.0 Quality Assurance for Ground-Based Remote Sensing Devices

Meteorological remote sensing provides an alternative to tower based measurements when the height of interest in an air quality study extends above the tower height. In addition, they provide measurements without disturbing the environment. They do not need the towers, bridges, or other structures in the environment that are needed by in-situ sensors. The remote sensing data are represented as a spatial, or more specifically, a volume average. Whereas in-situ sensors measure a particular meteorological variable by direct contact, and the data collected from the in-situ sensors provide the user with a point estimate of the variable in question.

11.1 Types of Remote Sensors

There are three types of commercially available remote sensors, SODAR (Sound Detection and Ranging), radar (Radio Detection And Ranging), and radar/RASS (Radio Acoustic Sounding System). SODAR uses acoustic pulses to measure horizontal and vertical wind profiles as well as the height above ground of the elevated inversion layer and mixed layer. Radar uses electromagnetic pulses to measure horizontal and vertical winds. Radar/RASS uses both acoustic and electromagnetic waves to measure virtual air temperature, wind speed and wind direction profiles. For more information on the three types of remote sensors, refer to the Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008). This can be found online:

https://www3.epa.gov/ttn/amtic/files/ambient/met/Volume_IV_Meteorological_Measurements.pdf

11.2 Acceptance Testing

Acceptance testing is performed on newly purchased or installed equipment to show that it is performing according to the manufacturer’s specifications. It should include comparison of data from the system to be tested with data from an acceptable in-situ sensor on a tower, tethersonde, a mini-sodar, kite, NWS rawinsonde, or similar systems. An in-situ sensor possesses the required sensitivity to determine if the remote sensing device is operating normally, even though it does not qualify as a transfer standard. For further information on acceptance testing, refer to the Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008).

11.3 Calibration and Performance Audit Methods

Calibration of meteorological remote sensing devices is problematic since there is no correspondence with calibration of in-situ instruments. Direct comparisons with rawinsondes, tether balloons, or instrument towers are not always adequate because of the difficulty in comparing point estimates with large volume estimates, as well as the problem of separation in time and space between the two platforms. Calibration and performance audit techniques should focus on the instrument electronics and other system components. If practical, the acceptance test should be repeated during the calibration process. This will ensure the highest quality data are being obtained.

For further information, refer to the Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008).

11.4 Operation, Maintenance, and Quality Control

Refer to the Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008), for information.

11.5 Estimating Accuracy and Precision

There are no accepted audit procedures to define system accuracy and precision of remote sensing devices.

12.0 PAMS Meteorological Monitoring Guidance

Photochemical Assessment Monitoring Stations (PAMS) are required by Title 40 Part 58 of the Code of Federal Regulations for ozone non-attainment areas which are classified as serious, severe, or extreme. The monitoring of surface and upper-air meteorological parameters is part of the monitoring requirement. Meteorology is a critical element in the formation, transport, and eventual destruction of ozone and its precursors. Consequently, meteorological data are essential to the development and evaluation of ozone control strategies. For information on PAMS site types, refer to the Technical Assistance Document for the Sampling and Analysis of Ozone Precursors (USEPA, September, 1998). This can be found online at:

https://www3.epa.gov/ttn/amtic/pamsmain.html

12.1 Upper-Air Meteorology

USEPA requires upper-air meteorological monitoring for each PAMS affected region. This monitoring is performed by the USEPA regional offices and some regional airports. Profiles of wind speed and wind direction are needed for use in transport and dispersion modeling. Profiles of air temperature are highly desired since this is a principle indicator of atmospheric stability. Other variables that can be measured, but not required, include vertical wind speed, relative humidity, and barometric pressure. USEPA currently does not have any specific guidance on measurement levels and accuracies for upper-air data. However, the WMO (World Meteorological Organization) has guidelines that can be used as a model by those agencies responsible for implementing PAMS upper-air measurements.

The upper-air measurements are intended for more micro-scale application than the surface meteorological measurements. Consequently, the location of the upper-air site does not necessarily need to be associated with any particular PAMS surface site. However, for convenience and logistics, the upper-air site can be collocated with a surface meteorology station. For additional information, including types of upper-air monitoring systems, refer to the Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008).

12.2 Surface Meteorology

The surface meteorological parameters that are measured at all sites in a PAMS network include horizontal wind speed and wind direction, ambient air temperature, and relative humidity. Measurement of solar radiation, ultraviolet radiation, barometric pressure, and precipitation are required at only one site in the PAMS network.

The meteorological instrumentation should not be mounted on or near solid structures such as buildings, stacks, water storage tanks, grain elevators, and cooling towers since they may create significant wind flow distortions. Instruments should be mounted on an open lattice 10 m tower. This type of structure creates the least amount of wind flow distortion. The type of tower may be fixed, tilt-over, or telescopic. The instruments must maintain a fixed orientation on the tower at all times. The siting of the tower/instruments should follow the guidelines stated in Section 1.4 of this chapter and in the Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008).

The recommended sampling interval of the meteorological sensors by the data acquisition system (DAS) is 10 seconds. Data for all variables should be processed to obtain one-hour averages. The observation time should correspond to the time at the end of the averaging period and should be recorded as local standard time. The DAS clock should have an accuracy of ±1 minute per week.

12.3 Wind Speed and Direction

Horizontal wind speed and wind direction measurements are essential to the evaluation of the transport and dispersion process, and important in assessing atmospheric stability and turbulence. Siting of the sensors can be found in Section 2.1 of this chapter and in the Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV, Meteorological Measurements, Version 2.0 (USEPA, March 2008).

A sensor with a high accuracy at low wind speeds and a low starting threshold is recommended for PAMS applications. Lightweight molded plastic or polystyrene foam should be employed for cups and propeller blades to achieve a starting threshold < 0.5 m/s. Wind vanes or tail fins should also be composed of lightweight molded plastic or polystyrene. The distance constant should be ≤ 5 m at standard sea level density. The starting threshold should be ≤ 0.5 m/s. The delay distance should be ≤ 5 m at standard sea level density. Overshoot must be $\leq 25\%$ and the damping ratio should lie between 0.4 and 0.7. See Section 3.0 for accuracy limits of the wind speed and direction sensors.

12.4 Air Temperature

Air temperature is strongly correlated with extreme ozone concentrations. There are several types of air temperature sensors as stated in Section 4.1. The platinum resistance temperature detectors provide accurate measurements with a stable calibration over a wide temperature range and are among the more popular sensors used in ambient monitoring for PAMS applications, the temperature sensor should be located 2 m above the ground and away from the tower a distance of at least one tower width from the closest point on the tower. For additional siting criteria, see Section 2.2.

For temperature measurements, the resolution should be 0.1 degrees Celsius with a time constant ≤ 60 seconds. The best type of shield provides forced aspiration at a rate of at least 3 m/s over a radiation range of -100 to +1100 W/m^2. Section 4.2.1 lists the accuracy requirements for these sensors.

12.5 Relative Humidity

Measurements of relative humidity are essential to understanding chemical reactions that occur between ozone precursors and water vapor. The sensor should be in the same aspirated radiation shield as the temperature sensor, and at a height of 2 m above the ground. For additional siting, see section 2.2 of this chapter. The accuracy of the sensor should be ±3% RH over a range of 10 to 95% RH and ±5% from 0 to 10% RH and 95 to 100 % RH. Resolution should be 0.5% RH with a time constant ≤ 60 seconds. Section 5.6.2 of this chapter lists the accuracy requirements for these sensors.

The thin-film elements of the humidity sensor must be protected from contaminates such as salt, hydrocarbons, and other particulate. These pollutants can easily corrupt the sensing element and lead to failure of the instrument. The best protection is the use of a porous membrane filter that allows the passage of ambient air and water vapor while keeping out particulate matter.

12.6 Solar Radiation

Solar radiation is a measure of the electromagnetic radiation of the sun and is represented as an energy flux. Solar radiation measurements are used in heat flux calculations, for estimating atmospheric stability, and in modeling photochemical reactions. Manufacturer's specifications for the pyranometer should match the World Meteorological Organization's requirements for either a secondary standard or first class pyranometer if reliable heat flux and stability parameters are to be calculated. Photovoltaic pyranometers should not be used for PAMS applications due to their spectral response being limited only to that of the visible spectrum. Resolution of the sensor should be 1 W/m^2 over a range of 0 to 1200 W/m^2 and a time constant ≤ 60 seconds. Siting requirements are listed in Section 2.3 of this chapter. See Sections 6.0 and 6.5.4 of this chapter for more details on solar radiation monitoring, and accuracy requirements for these sensors, respectively.

12.7 Ultraviolet Radiation

Ultraviolet pyranometers that have a spectral response spanning both the UV-A and UV-B ranges are recommended for PAMS applications. Resolution should be 0.01 W/m^2 over range 0-12 w/m^2 and a time constant ≤60 seconds. Siting requirements are listed in Section 2.0 of this chapter. See Sections 6.0 and 6.5.4 of this chapter for more details on UV radiation monitoring, and accuracy requirements for ultraviolet radiation sensors, respectively.

12.8 Precipitation

The rain gage should have a resolution of 0.25 mm and a time constant ≤60 seconds. Siting and accuracy requirements are listed in sections 2.4 and 7.3, respectively, of this chapter.

12.9 Barometric Pressure

Barometric pressure is useful for examining trends in the weather on the order of several days or more. It is also essential for the calculation of thermodynamic quantities such as air density, absolute humidity, and potential temperature.

The sensor can be placed at the base of the tower or inside a shelter. Ideally, the sensor should be placed at 2 m above the ground. If the pressure sensor is placed indoors, accommodations should be made to vent the pressure port to the outside environment. One end of a tube should be attached to the sensor’s pressure port and the other end vented to the outside of the trailer or shelter so that pressurization due to the air conditioning or heating system is avoided. The wind can often cause a significant change of pressure in a room where a sensor is located. When strong or gusty winds prevail, fluctuations on the order of 2 to 3 hectopascals (hPa) may occur. Most sensors are capable of measuring barometric pressure with an overall accuracy of ±1.0 hPa over a range of 800 to 1100 hPa, a resolution of 0.1 hPa, and a time constant ≤60 seconds. Section 8.2.2 lists the accuracy requirements for barometric pressure sensors.

Form 1
Wind Speed/Direction Siting Criteria

Site: ______________________ **AQS #:** ______________________

Date: ______________________ **Auditor:** ______________________

	Check if Okay	Comments
Sensors 10 meters above ground in open, level terrain	☐	- ______________________
Tower mounted sensors on boom which is twice as long as tower's diameter	☐	- ______________________
Boom directed into prevailing wind and secure	☐	- ______________________
Tower of tower mounted sensors open grid design	☐	______________________
Sensors on roofs–1.5 times the height of the building	☐	- ______________________
Tall buildings–10 to 15 foot mast on side of prevailing wind	☐	______________________

Sensor 10 times the height of any obstruction ☐ ______________________________

If on top of a tower, must be at least 1 tower diameter above the tower ☐ ______________________________

Diagram the location, height, and distance of the obstruction on the back of this sheet.
Remarks: ____
____

Form 2
Temperature Siting Criteria

Site: ________________________________ **AQS #:** ________________________________

Date: ________________________________ **Auditor:** ______________________________

	Check if Okay	Comments
Ground beneath sensor unwatered short grass or natural earth	☐	______________________________
Sensor above open, level ground 9 meters diameter	☐	______________________________
Sensor minimum 30 meters from large paved areas	☐	______________________________
Sensor away from large industrial heat sources, roof tops, steep slopes, hollows, high vegetation, swamps, snow drifts, standing water, and air exhausts	☐	______________________________
Mounting height (1.25 to 2 meters above ground for louvered shelters)	☐	______________________________
Tower mounted sensors on boom which is as long as towers diameter	☐	______________________________
Downward facing aspirated shield on sensor, if not, sensor should point north	☐	______________________________
Louvered instrument shelters oriented with door opening true north	☐	______________________________
Sensor located at 4 times the height of any obstructions	☐	______________________________

Diagram the location, height, and distance of the obstruction on the back of this sheet.
Remarks: ____

____

Form 3
Humidity Siting Criteria

Site: ______________________ **AQS #:** ______________________

Date: ______________________ **Auditor:** ______________________

	Check if Okay	Comments
Ground beneath sensor unwatered short grass or natural earth	☐	______________________
Sensor above open, level ground 9 meters diameter	☐	______________________
Sensor minimum 30 meters from large paved areas and standing water	☐	______________________
Sensor away from large industrial heat sources, roof tops, steep slopes, hollows, high vegetation, swamps, snow drifts, standing water, and air exhausts	☐	______________________
Mounting height (1.25 to 2 meters above ground for louvered shelters)	☐	______________________
Tower mounted sensors on boom which is as long as towers diameter	☐	______________________
Downward facing aspirated shield on sensor, if not, sensor should point north	☐	______________________
Louvered instrument shelters oriented with door opening true north	☐	______________________
Sensor located at 4 times the height of any obstructions	☐	______________________

Diagram the location, height, and distance of the obstruction on the back of this sheet.
Remarks: ____
____

Form 4
Solar Radiation Siting Criteria

Site: ______________________________ **AQS #:** ______________________________

Date: ______________________________ **Auditor:** ______________________________

	Check if Okay	Comments
Sensor free from horizontal obstruction (diagram below)	☐	______________________
Sensor away from light colored walls	☐	______________________
Sensor away from artificial sources of radiation	☐	______________________
Pyranometers located on a tall platform or roof	☐	______________________
Net radiometers mounted at least 1 meter above ground	☐	______________________

Diagram the location, height, and distance of the obstruction on the back of this sheet.
Remarks: ____
____

Form 5
Precipitation Siting Criteria

Site: ______________________________ **AQS #:** ______________________________

Date: ______________________________ **Auditor:** ______________________________

	Check if Okay	Comments
Mouth of rain gage mounted horizontal	☐	______________________________
Rain gage minimum 30 cm above ground	☐	______________________________
Surface around gage natural vegetation or gravel	☐	______________________________
Wind shield used if in open area	☐	______________________________
Collector minimum 100 meters from open storage of agricultural or fuel products	☐	______________________________
Collector away from overhead wires	☐	______________________________
Gage more than 100 meters from mobile pollution sources	☐	______________________________
Wet/Dry collectors parallel to prevailing wind	☐	______________________________
Wet bucket upwind of the dry bucket	☐	______________________________
Sensor two times the height of any obstruction	☐	______________________________

Diagram the location, height, and distance of the obstruction on the back of this sheet.
Remarks: ____
____

Form 6
Wind Speed Calibration (Met One)

Site:		**Performed By:**	
Date:		**Last Audit:**	
AQS #:		**Last Cal:**	
Start Time:		**End Time:**	

SENSOR INFORMATION

	Head		**Signal Conditioner**		**Wind Speed Module**
Mfg:	**Met One**	**Mfg:**	**Met One**	**Mfg:**	**NA**
Model:		**Model:**		**Model:**	**NA**
Serial #:		**Serial #:**		**Serial #:**	**NA**

RECORDING DEVICES

	Manufacturer:	**Model :**	**Serial #:**	**Range:**
Primary:	**ESC**	**8816 DATA LOGGER**		**MPH**
Secondary:	**YOKOGAWA**			**100%**

CONVERSION FACTOR

% chart x 1.118 = MPH
DVM x 22.36 = MPH
1 MPH = .44704 m/s

TEST RESULTS

Pre-Adjustment (As Found)

RPM	Act. (MPH)	Primary Response	Secondary Response	Meas. Value (MPH)	Diff. Meas.-Act. (MPH)
No Wind	0				
N/S Block	111.85				
E/W Block	111.85				

Form 6 Continued

DATA STATUS: __**Invalid or Valid Date**__

Adjustments made to unit? (circle one) Yes or No

Post- Adjustments not necessary

**If there were adjustments made,
was it on: (circle one)
Same unit or New Unit Required**

**If adjustment was made on same unit, fill out Post-Adjustment (As left).
If new unit required, include Serial Number here: ____________________.**

Post-Adjustment (As left)

RPM	Act. (MPH)	Primary Response	Secondary Response	Meas. Value (MPH)	Diff. Meas.-Act. (MPH)
No Wind	0				
N/S Block	111.85				
E/W Block	111.85				

Wind Speed Calibration (Weathertronics)

Site:		**Performed By:**	
Date:		**Last Audit:**	
AQS #:		**Last Cal:**	
Start Time:		**End Time:**	

Form 6 Continued

SENSOR INFORMATION

	Head		**Signal Conditioner**		**Wind Speed Module**
Mfg:	Weathertronics	**Mfg:**	Weathertronics	**Mfg:**	Weathertronics
Model:	2030	**Model:**		**Model:**	
Serial #:		**Serial #:**		**Serial #:**	

CONVERSION FACTOR

Stainless Steel cups: MPH= ((RPM/2) / 10.19) + .5299
Carbon-Graphite cups: MPH=((RPM/2) / 9.901) + .746
1 MPH = .44704 m/s

CALIBRATION STANDARD

Brand /Model:	**YOUNG / 18811**
Serial #:	**CA 02093**
Cert. Date:	

	Manufacturer	**Model**	**Serial #**	**Range**
Primary :	ESC	8816 Data Logger		MPH
Secondary:	YOKOGAWA			

TEST RESULTS

Pre-Adjustment (As Found)

Sensor Response

RPM	**Act. MPH Value SS / C-G**	**Primary Response**	**Secondary Response**	**Meas. Value (MPH)**	**Diff. Meas.-Act. (MPH)**
0	**0 / 0**				
100	**5.44 / 5.80**				
300	**15.25 / 15.90**				
600	**29.97 / 31.05**				
950	**47.14 / 48.72**				

Form 6 Continued

BEARING CHECK				
Bearing Torque:		**gm cm**	**Circle One:**	**Pass or Fail**
Limit:	**3.6**	**gm cm**	**If Fail, take appropriate action**	

Post-Adjustment (As left)

Sensor Response

RPM	Act. MPH Value SS / C-G	Primary Response	Secondary Response	Meas. Value (MPH)	Diff. Meas.-Act. (MPH)
0	0 / 0				
100	5.44 / 5.80				
300	15.25 / 15.90				
600	29.97 / 31.05				
950	47.14 / 48.72				

BEARING CHECK				
Bearing Torque:		**Gm cm**	**Circle One:**	**Pass or Fail**
Limit:	**3.6**	**Gm cm**	**If Fail, take appropriate action**	

Remarks: ______________________________
____

Form 7
Wind Direction Calibration (Weathertronics)

Date:		**Site:**	
Performed By:		**AQS #:**	
Start time:		**Last Cal:**	
End time:		**Last Audit:**	

SENSOR INFORMATION					
Head		**Signal Conditioner**		**Wind Speed Module**	
Mfg:	**Weathertronics**	**Mfg:**	**Weathertronics**	**Mfg:**	**Weathertronics**
Model:		**Model:**		**Model:**	
Serial #:		**Serial #:**		**Serial #:**	

RECORDING DEVICES				
	Manufacturer	**Model**	**Serial Number**	**Range**
Primary (DAS)				
Secondary				

REFERENCE POINT			
Object:		**Azimuth:**	

CALIBRATION RESULTS
Vane Orientation Pre-Adjustment (As Found)

	Azimuth	DVM Response	(DAS) Primary Response (V)	(Prm.) Meas. Value (Deg)	Secondary Resp. (%)	Diff. Meas.-Act
Vane to Ref. Pt.						
Vane from Ref. Pt.						

Form 7 Continued

BENCH LINEARITY CHECK

Degree Set	DVM Resp.	(DAS) Primary Resp. (V)	(Prm.) Meas. Value (Deg)	Secondary Resp. (%)	Diff. Meas.-Act
360					
450					
540/180					
270					
360					
270					
180					
90					
360					

BEARING CHECK

Bearing Torque: ____________________________ gm cm Circle One: Pass or Fail

Limit: ___________no known limit______________ gm cm If Fail, act. threshold: T = k/U2 =

Data Status:

Unit Status: Adjustments made to unit? Yes No

Bearings changed? Yes No

Circle one: Adjustment made: If yes, then circle one: Same unit or new unit required

No adjustment

If adjustments were made on the same unit, fill out Post-Adjustment below:
If new unit required, enter Serial Number here: _________________.

Form 7 Continued
BENCH LINEARITY CHECK
Post-Adjustment (As left)

Degree Set	DVM Resp.	(DAS) Primary Resp. (V)	(Prm.) Meas. Value (Deg)	Secondary Resp. (%)	Diff. Meas.-Act.
360					
450					
540/180					
270					
360					
270					
180					
90					
360					

BEARING CHECK

Bearing Torque: ____________________________ gm cm **Circle One: Pass or Fail**

Limit: __________no known limit________________ gm cm **If Fail, act. threshold: T = k/U2 =**

Vane Orientation Post-Adjustment (As left)

	Azimuth	DVM Resp.	(DAS) Primary Resp. (V)	(Prm.) Meas. Value (Deg)	Secondary Resp. (%)	Diff. Meas.-Act.
Vane to Ref. Pt.						
Vane from Ref. Pt.						

Remarks: ____

____

Form 8
Wind Speed Audit

Site: ________________________________ **Auditor:** ______________________________
Date: ________________________________ **Last Audit:** ___________________________
AQS #: _______________________________ **Last Cal:** _____________________________
Start Time: ___________________________ **End Time:** ____________________________

Sensor Information

-Head-
Mfg: ________________________________
Model: _______________________________
Serial #: _____________________________

-Signal Conditioner-
Mfg: _________________________________
Model: _______________________________
Serial #: _____________________________

Audit Standard Information

Brand/Model: ___________________**Serial #:**__________________ **Cert. Date:** _____________
Brand/Model: ___________________**Serial #:**__________________ **Cert. Date:** _____________

Audit Data

Primary Recording Device: ____________________ **Range:** ____________________
Secondary Recording Device ___________________ **Range:** ____________________
Digital Volt Meter: ___________________________ **Range:** ____________________

Audit Results

RPM	ACT. (MPH)	PRIMARY	SECONDARY	DVM	MEASURED (MPH)	DIFF. MPH (ACT. - MEAS.)

Bearing Check

Bearing Torque: _______________ **Limit:** ______________ **Pass:** ________ **Fail:** ________
Calibration/Data Status: _______**In Calibration, Data Valid**
(±.5 MPH up to 10 MPH, ±5% if > 10 MPH)
_______**Out of Calibration, Data Invalid**

Remarks: ____
____

Form 9
Wind Direction Audit

Site: ________________________ **Auditor:** ________________________
Date: ________________________ **Last Audit:** ________________________
AQS #: ________________________ **Last Cal:** ________________________
Start Time: ________________________ **End Time:** ________________________

Sensor Information

-Head-
Mfg: ________________________
Model: ________________________
Serial #: ________________________

-Signal Conditioner-
Mfg: ________________________
Model: ________________________
Serial #: ________________________

Audit Data

Primary Recording Device: ________________________ **Range:** ____________
Secondary Recording Device: ________________________ **Range:** ____________
Digital Volt Meter: ________________________ **Range:** ____________

Audit Results (as found)

Reference Point	Primary	Secondary	DVM	Measured Deg.	Deg. Difference

-Bench Linearity Check-

Set	Primary	Secondary	DVM	Measured Deg.	Deg. Difference

Bench Linearity Spread:

Audit Results (as left)

Reference Point	Primary	Secondary	DVM	Measured Deg.	Deg. Difference

Bearing Check

Bearing Torque: ____________ **Limit:** ____________ **Pass:** ________ **Fail:** ______
Calibration/Data Status: _______**In Calibration, Data Valid (±5 degrees)**
_______**Out of Calibration, Data Invalid**
Remarks: ____
____

Form 10
Outside Temperature Calibration

Performed By:		**AQS #:**	
Start Time:		**Last Cal.:**	
End Time:		**Last Audit:**	

SENSOR INFORMATION			
	Probe		**Signal Conditioner**
Mfg:		**Mfg:**	
Model:		**Model:**	
Serial #:		**Serial #:**	

	Mfg	**Model**	**Serial #**	**Range**
Primary (DAS)				
Secondary				
CALIBRATION STANDARD				
Brand/Model:		**Cert. Date:**		
Serial #:				

CALIBRATION RESULTS
Pre-Adjustment (As Found)

Std. Temp. ˚C	**˚F**	**DVM Response**	**Primary (DAS) Response (mV)**	**Meas. Resp. ˚C**	**˚F**	**Secondary (rec) (rec or % chart)**	**Diff Meas. - Std. ˚C**	**˚F**

must be within **±1.0 ˚C at SLAMS sites, ±0.5 ˚C at NCORE, PAMS, and PSD sites.**

Form 10 Continued

DATA STATUS:

Unit Status: **Adjustments made to unit?** **Yes** **No**

Probe free of corrosion? **Yes** **No**

Circle one: **No adjustment** **Adjustment made:**

If yes, then circle one: **Same unit** **or** **new unit required**

If adjustments were made on the same unit, fill out Post-Adjustment on the back.

If new unit required, fill out another outside temperature form.

CALIBRATION RESULTS
Post-Adjustment (As Left)

Std. Temp. ˚C	˚F	DVM Response	Primary (DAS) Response (mV)	Meas. Resp. ˚C	˚F	Secondary (rec) (rec or % chart)	Diff Meas. - Std. ˚C	˚F

must be within **±1.0 ˚C at SLAMS sites, ±0.5 ˚C at NCORE, PAMS, and PSD sites.**

Remarks: ____
____

Form 11
Outdoor Temperature Audit

Site: ______________________________ **Auditor:** ___________________________
Date: _____________________________ **Last Audit:** ________________________
AQS #: ____________________________ **Last Cal:** __________________________
Start Time: ________________________ **End Time:** _________________________

Sensor Information

-Head-
Mfg: ______________________________
Model: ____________________________
Serial #: ___________________________

-Signal Conditioner-
Mfg: ______________________________
Model:
Serial #: ___________________________

Audit Standard Information
Brand/Model: _______________________ **S.N.** _______________**Cert. Date:** __________

Audit Data

Primary Recording Device: ________________________ **Range:** ____________________
Secondary Recording Device: ______________________ **Range:** ____________________
Digital Volt Meter: ______________________________ **Range:** ____________________

Audit Results

Std. Temp	Primary	Secondary	DVM	Meas. Temp	˚C Diff. Meas. – Std.

Calibration/Data Status: ________ **In Calibration Data Valid (-.5 to +5 °C)**
________ **Out of Calibration, Data Invalid**

Remarks: ____
____

Form 12
Dew point Calibration

Date:		**Site:**	
Perf. By:		**AQS #:**	
Start time:		**Last Cal.:**	
End time:		**Last Audit:**	

SENSOR INFORMATION

Probe		**Signal Conditioner**	
Mfg:	**Young**	**Mfg:**	**Young**
Model:		**Model:**	
Serial #:		**Serial #:**	

RECORDING DEVICES

	Mfg.	**Model**	**Serial Number**	**Range**
Primary (DAS)				
Secondary				

CALIBRATION STANDARD

Model/Serial #: **Certification Date:**

CALIBRATION RESULTS
PSYCHROMETER COMPARISON
Pre-Adjustment (As Found)

Std. Dry Bulb (˚F)	**Std. Wet Bulb (˚F)**	**Actual DP ˚C**	**˚F**	**Primary Response (mV)**	**Meas. Resp. ˚C**	**˚F**	**Secondary Response (˚F)**	**Diff. Meas -Std ˚C**	**˚F**

***must be within* ±1.5 ˚C DP**

Form 12 Continued

DATA STATUS:

Unit Status: **Adjustments made to unit?** **Yes** **No**

Multi-plate radiation shield clean? **Yes** **No**

Circle one: **No adjustment** **Adjustment made**

If yes, then circle one: **Same unit or new unit required**

If adjustments were made on the same unit, fill out Post-Adjustment on the back.

If new unit required, fill out another outside temperature form.

CALIBRATION RESULTS
PSYCHROMETER COMPARISON
Post-Adjustment (As Left)

Std. Dry Bulb (˚F)	Std. Wet Bulb (˚F)	Actual DP ˚C	˚F	Prim (DAS) Resp. (mV)	Meas. Resp. ˚C	˚F	Secondary Response ˚F	Diff. Meas -Std ˚C	˚F

must be within **±1.5 ˚C DP**

Remarks: ____

____

Form 13
Relative Humidity Calibration

Date:		**Site:**	
Perf. By:		**AQS #:**	
Start time:		**Last Cal:**	
End time:		**Last Audit:**	

SENSOR INFORMATION

Probe		**Signal Conditioner**	
Mfg:	**Young**	**Mfg:**	**Young**
Model:		**Model:**	**NA**
Serial #:		**Serial #:**	**NA**

RECORDING DEVICES

	Manufacturer	**Model**	**Serial Number**	**Range**
Primary (DAS):				
Secondary:				

CALIBRATION STANDARD

Model/Serial #:		**Cert. Date:**	

As Found Air Check

Standard % RH	**Measured % RH**	**Difference (Meas. - Std.)**
48.6	**49.2**	0.6

Chamber Check

Chamber Set	**Standard RH**	**Measured RH**	**Difference (Meas. - Std.)**
20.00			**0.00**
50.00			**0.00**
90.00			**0.00**

Must be within +/- 5% RH for PAMS, +/- 7% RH for NCORE, +/- 10% RH for SLAMS/SPM

Form 13 Continued

DATA STATUS:

Unit Status: Adjustments made to unit? Yes No

Sensor shield clean? Yes No

Circle one: No adjustment Adjustment made:

If yes, then circle one: Same unit or new unit required

If adjustments were made on the same unit, fill out Post-Adjustment on the back.

If new unit required, include Serial Number here._________________

As Found Air Check

Standard % RH	Measured % RH	Difference (Meas. - Std.)
48.6	49.2	0.6

Chamber Check

Chamber Set	Standard RH	Measured RH	Difference (Meas. - Std.)
20.00			0.00
50.00			0.00
90.00			0.00

Must be within +/- 5% RH for PAMS, +/- 7% RH for NCORE, +/- 10% RH for SLAMS/SPM

Remarks: ____

Form 14
Dew Point Audit

Site: ________________________________ **Auditor:** ____________________
Date: _______________________________ **Last Audit:** __________________
AQS #: ______________________________ **Last Cal:** ____________________
Start Time: __________________________ **End Time:** ___________________

Sensor Information

-Head-
Mfg: ________________________________
Model: ______________________________
Serial #: _____________________________

-Signal Conditioner-
Mfg: ________________________________
Model: ______________________________
Serial #: ___________________________

Audit Standard Information

Brand/Model: __________________ **Serial #:** __________________ **Cert. Date:** _________

Audit Data

Primary Recording Device: ______________________ **Range:** _______________________
Secondary Recording Device: ____________________ **Range:** _______________________
Digital Volt Meter: _____________________________ **Range:** _______________________

Audit Results

Wet Bulb	Dry Bulb	Std. DP	Primary	Secondary	DVM	Measured DP	Deg. C Diff.

Calibration/Data Status: ________ **In Calibration, Data Valid (-1.5 to +1.5 Deg. C DP)**
________ **Out of Calibration, Data Invalid**

Remarks:
____
____

Form 15
Relative Humidity Audit

Site: ________________________________ **Auditor:** ____________________
Date: _______________________________ **Last Audit:** __________________
AQS #: ______________________________ **Last Cal:** ____________________
Start Time: __________________________ **End Time:** ___________________

Sensor Information

-Head-
Mfg: ________________________________
Model: ______________________________
____
Serial #: _____________________________

-Signal Conditioner-
Mfg: ______________________________
Model:
Serial #: ___________________________

Audit Standard Information

Brand/Model: __________________ **Serial #:** __________________ **Cert. Date:** ________

Audit Data

Primary Recording Device: ______________________ **Range:** _______________________
Secondary Recording Device: ___________________ **Range:** _______________________
Digital Volt Meter: _____________________________ **Range:** _______________________

Audit Results

As Found **Air Check**

Standard % RH	Measured % RH	Difference (Meas. - Std.)
48.6	**49.2**	0.6

Chamber Check

Chamber Set	Standard RH	Measured RH	Difference (Meas. - Std.)
20.00			**0.00**
50.00			**0.00**
90.00			**0.00**

Must be within +/- 5% RH for PAMS, +/- 7% RH for NCORE, +/- 10% RH for SLAMS/SPM

Form 16
Ultra-Violet Radiometer Calibration

County:		**City:**	
Site:		**AQS #:**	
Date:		**Initials:**	
Start Time:		**Last Cal:**	
End Time:		**Last Audit:**	

FIELD SENSOR INFORMATION			**COMPARISON (QA) SENSOR INFORMATION**	
Manufacturer:	**Eppley Laboratory**		**Manufacturer:**	**Eppley Laboratory**
Model #:			**Model#:**	
Serial #:			**Serial #:**	
Mfg. Cal. Date:			**Mfg. Cal. Date:**	
Conversion Value:			**Conversion Value:**	
RECORDING DEVICES				
	Mfg.	**Model**	**Serial #**	**Range**
Primary DAS):				
Secondary:				

Form 16 Continued
TEST RESULTS

Pre-Adjustment (As Found)
Sensor Response

Hour or Peak Value	Field Sensor Primary Unit Response		Field Sensor Secondary Unit Response		Comparison Sensor Primary Unit Response		Comparison Sensor Secondary Unit Response		Diff. field-comp. (in mcal)	(optional) % difference if > 10
	mV	mcal	mV	mcal	mV	mcal	mV	mcal		

DATA STATUS:

(Circle one)

Recalculation of conversion needed? **Yes or No**

Silica gel good? **Yes or No**

Unit level? **Yes or No**

(Circle one)

Recalculation of conversion needed? **Yes or No**

Silica gel good: **Yes or No**

Unit level? **Yes or No**

Form 17
Radiation Audit

Site: ________________________________ **Auditor:** ______________________
Date: ________________________________ **Last Audit:** ____________________
AQS #: _______________________________ **Last Cal:** ______________________
Start Time: ___________________________ **End Time:** _____________________

Field Sensor Information

Mfg: ______________________________
Model: ____________________________
Serial #: ___________________________
Mfg. Cal. Date: _____________________
Conv. Value: ________________________

Audit Standard Information

Brand/Model: ______________________ **Serial #:** _______________ **Cert. Date:**_________
Mfg. Cal. Date: _____________________ **Conv. Value:** _______________________________

Audit Data

Primary Recording Device: __________________________ **Range:** ___________________
Secondary Recording Device: ________________________ **Range:** ___________________
Digital Volt Meter: __________________________________ **Range:** ___________________

Audit Results
(mmHg or mb)

Standard	Primary	Secondary	DVM	Measured	Per. Diff.

Calibration/Data Status: ________ **In Calibration Data Valid (±5%)**
________ **Out of Calibration, Data Invalid**

Remarks: ____
____

Form 18
Precipitation Audit

Site: ______________________________ **Auditor:** ____________________
Date: ______________________________ **Last Audit:** __________________
AQS #: _____________________________ **Last Cal:** ____________________
Start Time: _________________________ **End Time:** ___________________

Sensor Information

-Head-
Mfg: ______________________________
Model: _____________________________
____
Serial #: ___________________________

-Signal Conditioner-
Mfg: ______________________________
Model:
Serial #: ___________________________

Audit Standard Information

Brand/Model: ________________________ **S.N.** _______________**Cert. Date:** __________

Audit Data

Primary Recording Device: ________________________ **Range:** ________________
Secondary Recording Device: _______________________ **Range:** ________________
Digital Volt Meter: ___________________________________ **Range:** ________________

Audit Results

Number of Tips Measured	Standard Number of Tips	Percent Difference $\frac{\text{Measured} - \text{Std.}}{\text{Std.}} \times 100$

Calibration/Data Status: ________ **In Calibration Data Valid (±10%)**
________ **Out of Calibration, Data Invalid**

Form 19
Barometric Pressure (BP) Calibration

Date:		**Site:**	
Performed By:		**AQS #:**	
Start time:		**Last Cal.:**	
End time:		**Last Audit:**	

SENSOR INFORMATION					
Manufacturer:	**Novalynx**	**Model:**	**230-700N**	**Serial #:**	

RECORDING DEVICES

	Manufacturer	**Model**	**Serial #**	**Range**
Primary (DAS):				
Secondary:				

Conversion Factor

% of Chart x 3 + 800 = Barometric Pressure in mb

Calibration Standard

mb x 7.5 = mmHg

Brand/Model: ____________
Serial #: _________________
Certification Date: ________

TEST RESULTS
Pre-Adjustment (As Found)

BP standard (in mb)	**DVM Resp.**	**(DAS) Primary Resp. (V)**	**Actual BP Measured (in mb)**	**Secondary Resp. (%)**	**Diff. Meas.-Act.**

To be in calibration, difference must be within +/- 3 mb for NCORE and SLAMS, +/- 1 hPa for PAMS

DATA STATUS:

Unit Status: **Adjustments made to unit?:** **(circle one) Yes or No**

Screen hole on bottom of box clean?: **(circle one) Yes or No**

Form 19 Continued

No Adjustment **(Circle One): Yes or No**
Post-Adjustment not necessary **(Circle One): Yes or No**

If there were adjustments made,
was it on: **(Circle One) Same unit or New Unit**
Required

If adjustments were made on same unit, fill out Post-Adjustment (As left).
If new unit is required, include Serial Number here: ____________________.

Post-Adjustment (As left)

BP Standard (in mb)	DVM Resp.	(DAS) Primary Resp. (V)	Actual BP Measured (in mb)	Secondary Resp. (%)	Difference Measured-Actual

To be in calibration, difference must be within 3 mb for NCORE and SLAMS, +/- 1 hPa for PAMS

Remarks:
____
____
____
____

Form 20
Barometric Pressure Audit

Site: ______________________________ **Auditor:** ______________________________
Date: ______________________________ **Last Audit:** ___________________________
AQS #: _____________________________ **Last Cal:** _____________________________
Start Time: _________________________ **End Time:** _____________________________

Sensor Information

-Head- **-Signal Conditioner-**

Mfg: ______________________________ **Mfg:** ________________________________
Model: ____________________________ **Model:**

Serial #: ___________________________ **Serial #:**
____

Audit Standard Information

Brand/Model: ________________________ **S.N.** ______________**Cert. Date:** __________

Audit Data

Primary Recording Device: _________________________ **Range:** ____________________
Secondary Recording Device: _______________________ **Range:** ___________________
Digital Volt Meter: ________________________________ **Range:** ____________________
Units: ____

Audit Results
(mmHg or mb)

Standard	Primary	Secondary	DMV	Measured	Difference

Calibration/Data Status: ________ **In Calibration Data Valid (±2.25 mmHg, ±3 mb)**
________ **Out of Calibration, Data Invalid**

Remarks:
____
____
____
____

Table 1
Classification of Pyranometers According to Physical Response Characteristics

Sensor (mW/cm^2)		Temperature (%)	Linear (%)	Max Time Constant (sec)	Cosine Response (%)
1st Class	±0.1	±1	±1	25	±3
2nd Class	±0.5	±2	±2	60	±5.7
3rd Class	±1.0	±5	±3	240	±10