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Meteorological Monitoring Guidance for Regulatory Modeling Applications

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for Regulatory Modeling Applications

U.S. ENVIRONMENTAL PROTECTION AGENCY
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PREFACE

This document updates the June 1987 EPA document, "On-Site Meteorological Program Guidance for Regulatory Modeling Applications", EPA-450/4-87-013. The most significant change is the replacement of Section 9 with more comprehensive guidance on remote sensing and conventional radiosonde technologies for use in upper-air meteorological monitoring; previously this section provided guidance on the use of sodar technology.   The other significant change is the addition to Section 8 (Quality Assurance) of material covering data validation for upper-air meteorological measurements. These changes incorporate guidance developed during the workshop on upper-air meteorological monitoring in July 1998.

Editorial changes include the deletion of the "on-site" qualifier from the title and its selective replacement in the text with "site specific"; this provides consistency with recent changes in Appendix W to 40 CFR Part 51. In addition, Section 6 has been updated to consolidate and provide necessary context for guidance in support of air quality dispersion models which incorporate boundary layer scaling techniques.

The updated document (like the June 1987 document) provides guidance on the collection of meteorological data for use in regulatory modeling applications. It is intended to guide the EPA Regional Offices and States in reviewing proposed meteorological monitoring plans, and as the basis for advice and direction given to applicants by the Regional Offices and States. To facilitate this process, recommendations applicable to regulatory modeling applications are summarized at the end of each section. Alternate approaches, if these recommendations can not be met, should be developed on a case-by-case basis in conjunction with the Regional Office.

ACKNOWLEDGMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1   Background

This document provides guidance for the collection and processing of meteorological data for general use in air quality modeling applications. Such applications include those required in support of air quality regulations as specified in the Guideline on Air Quality Models. Guidance which specifically relates to a regulatory application is so indicated; in addition, recommendations affecting regulatory modeling applications are summarized at the end of individual sections.

Guidance is provided for the in situ monitoring of primary meteorological variables (wind direction, wind speed, temperature, humidity, pressure, and radiation) for remote sensing of winds, temperature, and humidity, and for processing of derived meteorological variables such as stability, mixing height, and turbulence. Most of the guidance is generic in that it supports most categories of air quality models including: steady-state, non-steady-state, Gaussian, and non-Gaussian models. However, material in some sections is probably more useful in support of some types of models than others. For example, the primary focus of the guidance on site selection (Section 3) is the collection of data at single locations for support of steady-state modeling applications. Non-steady-state modeling applications generally require gridded meteorological data using measurements at multiple sites. Support for such applications is provided to the extent that this guidance may be used for selecting sites to monitor the significant meteorological regimes that may need to be represented in these applications. Site selection criteria in these cases must be evaluated in concert with the objectives of the overall network; this falls in the category of network design and is beyond the scope of this document. Similarity, though generically useful, the guidance on upper-air meteorological monitoring (Section 9) is perhaps most useful in support of applications employing gridded meteorological data bases.

One of the most important decisions in preparing for an air quality modeling analysis involves the selection of the meteorological data base; this is the case whether one is selecting a site for monitoring, or selecting an existing data base. These decisions almost always lead to similar questions: "Is the site (are the data) representative?" This question is addressed in Section 3.1.

Minimal guidance is provided on the use of airport data; e.g., for use in filling gaps in site-specific data bases (Section 6.8). For practical purposes, because airport data were readily available, most regulatory modeling was initially performed using these data; however, one should be aware that airport data, in general, do not meet this guidance. The significant deviations to this guidance are discussed in Section 6.7.

The following documents provide necessary background and documentation for this guidance and are incorporated by reference: "Guideline on Air Quality Models" as published in Appendix W to 40 CFR Part 51 [1]; "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume IV. Meteorological Measurements" [2]; "On-site

Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources" **[3]**, "Standard for Determining Meteorological Information at Nuclear Power Sites" **[4]**.

1.2 Organization of Document

Section 2 provides general information on the instruments used for in-situ measurements of wind speed, wind direction, temperature, temperature difference, humidity, precipitation, pressure, and solar radiation. These variables are considered primary in that they are generally measured directly.

Section 3 provides guidance on siting and exposure of meteorological towers and sensors for the in-situ measurement of the primary meteorological variables. Specific guidance is provided for siting in simple terrain (Section 3.2), complex terrain (Section 3.3), coastal locations (Section 3.4), and urban locations (Section 3.5). The issue of representativeness is addressed in Section 3.1.

Section 4 provides guidance for recording of meteorological data.

Section 5 provides guidance on system performance.

Section 6 provides guidance for processing of meteorological data.

Section 7 provides guidance on data reporting and archiving.

Section 8 provides guidance on the quality assurance and quality control.

Section 9 provides guidance for the most widely used technologies employed for monitoring upper-air meteorological conditions; these include radiosondes and ground-based remote sensing platforms: sodar (Sound Detection and Ranging), radar (Radio Detection and Ranging), and RASS (Radio Acoustic Sounding System).

References are listed in Section 10.

2. PRIMARY METEOROLOGICAL VARIABLES

This section provides general information on the instruments used for in situ measurements of wind speed, wind direction, temperature, temperature difference, humidity, precipitation, pressure, and solar radiation. These variables are considered primary in that they are generally measured directly. Derived variables, such as atmospheric stability, mixing height, and turbulence are discussed in Section 6. Remote sensing platforms for measurements of winds, temperature, and humidity are discussed in Section 9; these variables, when determined using remote sensing, are not measured directly, but are derived from other measurements.

The choice of an instrument for a particular application should be guided by the data quality objectives of the application; as a minimum, these objectives should include the accuracy and resolution of the data needed by the application - recommended data quality objectives for regulatory dispersion modeling applications are provided in Section 5.0. Other considerations which may compete with the data quality objectives include the cost of the instrument, the need for and cost of routine maintenance, and the competing needs of ruggedness and sensitivity. One should also note that the cost of a successful monitoring program does not end with the purchase of the sensors; depending on the instrument, additional costs may be incurred for signal conditioning and recording hardware. There are also the costs involved in siting, installation, and calibration of the equipment, as well as costs associated with the quality assurance and processing of the data.

The focus in the following is on those classes of instruments that are considered best suited for routine in situ monitoring programs, and which generally have had the widest use. Additional information and illustrations for the instruments described in this section may be found in references [2], [5], [6], [7], and [8].

2.1   Wind Speed

Although wind is a vector quantity and may be measured and processed as such, it is common to measure and/or process the scalar components of the wind vector separately; i.e., wind speed (the magnitude of the wind vector) and wind direction (the orientation of the wind vector). Wind speed determines the amount of initial dilution experienced by a plume, and appears in the denominator of the steady-state Gaussian dispersion equation (in the non-steady-state puff model, the wind speed determines the plume/puff transport). In addition, wind speed is used in the calculation of plume rise associated with point source releases, to estimate aerodynamic effects in downwash calculations, and, in conjunction with other variables, in the determination of atmospheric stability (Section 6.4.4). Instruments used for in situ monitoring of wind speed are of two types: those which employ mechanical sensors (e.g., cup and propeller anemometers) and those which employ non-mechanical sensors (hot wire anemometers and sonic anemometers). The non-mechanical sensors are beyond the scope of this guidance and are not addressed in the following; however, this should not preclude their use. When these types of instruments are to be used in support of regulatory actions, prior approval should be obtained

from the reviewing authority as to how the data will be collected, processed, and quality assured. Guidance on the use of remote sensing platforms for measuring wind speed is provided in Section 9.

2.1.1   Cup Anemometers

The rotating cup anemometer consists of three, four, and sometimes six hemispherical or cone-shaped cups mounted symmetrically about a vertical axis of rotation. The three cup anemometer is recommended; this design has been shown to exert a more uniform torque throughout a revolution. The rate of rotation of the cups is essentially linear over the normal range of measurements, with the linear wind speed being about 2 to 3 times the linear speed of a point on the center of a cup, depending on the dimensions of the cup assembly and the materials from which the sensor is made **[5]**. Sensors with high accuracy at low wind speeds and a low starting threshold should be used (see Section 5). Light weight materials (e.g., molded plastic or polystyrene foam) should be employed to achieve a starting threshold (lowest speed at which a rotating anemometer starts and continues to turn when mounted in its normal position) of $\leq$ 0.5 m/s.

2.1.2   Vane-oriented and Fixed-mount Propeller Anemometers

The vane-oriented propeller anemometer usually consists of a two, three or four-balded propeller which rotates on a horizontal pivoted shaft that is turned into the wind by a vane. Most current versions of this type of anemometer use propellers that are based on a modified helicoid. The dynamic characteristics of the vane should be matched with those of the propeller.

There are several propeller anemometers which employ lightweight molded plastic or polystyrene foam for the propeller blades to achieve threshold speeds of $\leq$ 0.5 m/s. This type of anemometer may be applied to collecting mean wind speeds for input to models to determine dilution estimates and/or transport estimates. Because of their relatively quick response times, some having distance constants of about one meter, these sensors are also suitable for use in determining the standard deviation of the along-wind-speed fluctuations, σ_u. Care should be taken, however, in selecting a sensor that will provide an optimal combination of such characteristics as durability and sensitivity for the particular application.

The variation of output speed with the approach angle of the wind follows nearly a cosine response for some helicoid propeller anemometers. This relationship permits the use of two orthogonal fixed-mount propellers to determine the vector components of the horizontal wind. A third propeller with a fixed mount rotating about a vertical axis may be used to determine the vertical component of the wind, and also the standard deviation of the vertical wind, σ_w. It should be noted that deviation of the response from a true cosine for large approach angles (e.g., 80-90°) may lead to underestimations of the vertical wind component without special calibration of the output signal. Users of vertical propeller anemometers should consult with the manufacturer on proper handling of the data.

2.1.3　Wind Speed Transducers

There are several mechanisms that can be used to convert the rate of the cup or propeller rotations to an electrical signal suitable for recording and/or processing. The four most commonly used types of transducers are the DC generator, the AC generator, the electrical-contact, and the interrupted light beam. Many DC and AC generator types of transducers in common use have limitations in terms of achieving low thresholds and quick response times. Some DC generator transducers are limited because the combined effect of brush and bearing friction give a threshold speed above 0.5 m/s (above 1.0 mph). However, some anemometers employ miniaturized DC generators which allow thresholds below 0.5 m/s to be achieved. The AC generator transducers eliminate the brush friction, but care must be exercised in the design of the signal conditioning circuitry to avoid spurious oscillations in the output signal that may be produced at low wind speeds. Electrical-contact transducers are used to measure the "run-of-the-wind"; i.e., the amount of air (measured as a distance) passing a fixed point in a given time interval; wind speed is calculated by dividing run-of-the-wind measurements by the time interval. The interrupted light beam (light chopping) transducer is frequently used in air quality applications because of the lower threshold that can be achieved by the reduction in friction. This type of transducer uses either a slotted shaft or a slotted disk, a photo emitter and a photo detector. The cup or propeller assembly rotates the slotted shaft or disk, creating a pulse each time the light passes through a slot and falls on the photo detector. The frequency output from this type of transducer is handled in the same way as the output from an AC generator. Increasing the number of slots to about 100, thereby increasing the pulse rate, eliminates signal conditioning problems which may arise with lower frequencies. The frequency output from an AC generator or a light chopping transducer may be transmitted through a signal conditioner and converted to an analog signal for various recording devices, such as a continuous strip chart or a multi point recorder, or through an analog-to-digital (A/D) converter to a microprocessor type of digital recorder. Several modern data loggers can accept the frequency type signal directly, eliminating the need for additional signal conditioning. The recording and processing of the data are covered in more detail in Sections 4.0 and 6.0, respectively.

2.2　Wind Direction

Wind direction is generally defined as the orientation of the wind vector in the horizontal. Wind direction for meteorological purposes is defined as the direction from which the wind is blowing, and is measured in degrees clockwise from true north. Wind direction determines the transport direction of a plume or puff in air quality modeling applications. The standard deviation of the wind direction, σ_A, or the standard deviation of the elevation angle, σ_E, may also be used, in conjunction with wind speed, to derive the atmospheric stability category (Section 6.4). Wind direction may be measured directly using a wind vane (Section 2.2.1) or may be derived from measurements of wind speed components (Section 2.2.2).

2.2.1 Wind Vanes

The conventional wind vane consists of a tail section attached to one end of a horizontal shaft which, in turn, is mounted on a vertical axis; the tail and shaft rotate in a horizonal plane. The wind vane measures the azimuth angle of the wind. Wind vanes and tail fins should be constructed from light weight materials. The starting threshold (lowest speed at which a vane will turn to within 5° of the true wind direction from an initial displacement of 10°) should be ≤ 0.5 ms^{-1}. Overshoot must be ≤ 25% and the damping ratio should lie between 0.4 and 0.7.

Bi-directional vanes (bivanes) measure both the azimuth and elevation angles of the wind vector. The bivane generally consists of either an annular fin or two flat fins perpendicular to each other, counterbalanced and mounted on a gimbal so that the unit can rotate freely both horizontally and vertically. Bivanes require greater care and are not generally suited for routine monitoring. Data from bivanes, consequently, should only be used on a case by case basis with the approval of the reviewing authority.

2.2.2 U-V and UVW Systems

Another method of obtaining the horizontal and/or vertical wind direction is through the use of orthogonal fixed-mount propeller anemometers, the U-V or UVW systems. The horizontal and, in the case of UVW systems, the vertical, wind direction can be determined computationally from the orthogonal wind speed components. The computational methods are based on the fact that the variation of output speed with the approach angle of the wind follows nearly a cosine response for some helicoid propeller anemometers.

2.2.3 Wind Direction Transducers

Many kinds of simple commutator type transducers utilize brush contacts to divide the wind direction into eight or 16 compass point sectors. However, these transducers do not provide adequate resolution to characterize transport for most air quality modeling applications.

A fairly common transducer for air quality modeling applications is a 360° potentiometer. The voltage across the potentiometer varies directly with the wind direction. A commonly used solution to the discontinuity that occurs across the small gap in a single potentiometer is to place a second potentiometer 180° out of phase with the first one **[5]**. In this case the voltage output corresponds to a 0° to 540° scale. This transducer utilizes a voltage discriminator to switch between the "upper" and "lower" potentiometers at appropriate places on the scale. This technique eliminates chart "painting" which occurs on strip chart recorders when the wind oscillates across north (i.e., between 0 and full scale). A disadvantage is that chart resolution is reduced by one third.

Another type of transducer being used is a wind direction resolver, which is a variable phase transformer where the phase change is a function of the shaft rotation angle. This system alleviates the maintenance problems associated with the friction caused by the wiper in a

potentiometer; however, this type of transducer is more expensive and requires more complex signal conditioning circuity.

2.2.4   Standard Deviation and Turbulence Data

The standard deviation of the azimuth and elevation angles of the wind vector, σ_A and σ_E, respectively can be related to the dispersive capabilities of the atmosphere, in particular, to the dispersion coefficients σ_y and σ_z which characterize plume concentration distributions in commonly-used Gaussian models. These quantities can be used as inputs to algorithms to determine Pasquill stability categories (see Section 6.4.4), or may also be treated as turbulence data for direct input to certain Gaussian models. The σ values should be computed directly from high-speed analog or digital data records (Section 6.1). If a sigma meter or sigma computer is used, care should be taken that the results are not biased by smoothing of the data, and to ensure that the methods employed accurately treat the $0\text{-}360°$ crossover and use an adequate number of samples (at least 360 per averaging period, see Section 6.1.4). The comparability of results from the sigma computer to the direct statistical approach should be demonstrated. To accurately determine σ_A and σ_E, the wind direction sensors must possess certain minimum response characteristics. The most important in this regard is the damping ratio, which should be between 0.4 to 0.7 (see Section 5.2). The wind direction should also be recorded to a resolution of 1 degree in order to calculate the standard deviation.

2.3   Temperature and Temperature Difference

This section addresses both the measurement of ambient air temperature at a single level and the measurement of the temperature difference between two levels. The ambient temperature is used in determining the amount of rise experienced by a buoyant plume. The vertical temperature difference is used in calculating plume rise under stable atmospheric conditions, and is also used in determining Monin-Obukhov length, a stability parameter (Section 6.4.5).

2.3.1   Classes of Temperature Sensors

Sensors used for monitoring ambient temperature include: wire bobbins, thermocouples, and thermistors. Platinum resistance temperature detectors (RTD) are among the more popular sensors used in ambient monitoring; these sensors provide accurate measurements and maintain a stable calibration over a wide temperature range. The RTD operates on the basis of the resistance changes of certain metals, usually platinum or copper, as a function of temperature. These two metals are the most commonly used because they show a fairly linear increase of resistance with rising temperature **[5]**. "Three wire" and "four wire" RTDs are commonly used to compensate for lead resistance errors. A second type of resistance change thermometer is the thermistor, which is made from a mixture of metallic oxides fused together. The thermistor generally gives a larger resistance change with temperature than the RTD. Because the relation between resistance and temperature for a thermistor is non-linear, systems generally are designed

to use a combination of two or more thermistors and fixed resistors to produce a nearly linear response over a specific temperature range **[5, 8]**.

Thermoelectric sensors work on the principle of a temperature dependent electrical current flow between two dissimilar metals. Such sensors, called thermocouples, have some special handling requirements for installation in order to avoid induction currents from nearby AC sources, which can cause errors in measurement **[5]**. Thermocouples are also susceptible to spurious voltages caused by moisture. For these reasons, their usefulness for routine field measurements is limited.

2.3.2   Response Characteristics

The response of temperature sensors can be characterized by a first order linear differential equation. The time constant for temperature sensors, i.e. the time taken to respond to 63% of a step change in the temperature, is a function of the air density and wind speed or ventilation rate. The time constant for a mercury-in-glass thermometer is about l minute for a ventilation rate of 5 m/s **[5, 6]**. Time constants for platinum resistance temperature detectors (RTDs) and for thermistors mounted in a typical probe are about 45 seconds. These are adequate response times for monitoring programs (see Section 5.2).

2.3.3   Temperature Difference

The basic sensor requirements for measuring vertical temperature difference are essentially the same as for a simple ambient temperature measurement. However, matched sensors and careful calibration are required to achieve the desired accuracy of measurement. The ambient temperature measurement is often taken from one of the sensors used to measure the differential temperature. A number of systems are commercially available that utilize a special translator module to process the signal difference between the two component sensors. Through signal processing, the accuracy of the differential temperature can be calibrated to the level of resolution of the component systems.

2.3.4   Sources of Error

One of the largest sources of error in any temperature system is due to solar radiation. Temperature sensors must be adequately shielded from the influences of direct or reflected solar radiation in order to provide representative measurements. A well ventilated shelter may be adequate for surface temperature measurements but would be impractical for levels higher than a few meters above ground. Tower-mounted sensors are generally housed in aspirated radiation shields. It is advisable to utilize motor driven aspirators to ensure adequate ventilation. Care should also be taken that moisture not be allowed to come in contact with the sensor or the inside surfaces of the radiation shield. In some sensors moisture will change the electrical properties of the sensor, causing error. In others, the evaporative cooling will cause the temperature reading to

be too low. For temperature difference measurements, sensors should be housed in identical aspirated radiation shields with equal exposures.

2.4   Humidity

2.4.1   Humidity Variables

Humidity is a general term related to the amount of moisture in the air; humidity variables include vapor pressure, dew point temperature, specific humidity, absolute humidity, and relative humidity. With the exception of relative humidity, all of the above variables provide a complete specification of the amount of water vapor in the air; in the case of relative humidity, measurements of temperature and pressure are also required. Humidity is an important variable in determining impacts from moist sources, such as cooling towers; it is also used in modeling ozone chemistry.

2.4.2   Types of Instrumentation

There are basically two types of sensors for measuring humidity, psychrometers and hygrometers. The psychrometer, consists of two thermometers, one of which is covered with a wet wick (the wet bulb) and a mechanism for ventilating the pair. Evaporation lowers the temperature of the wet bulb; the difference in temperature from the dry bulb (the wet bulb depression) is a measure of the amount of moisture in the air. While still in use at many observing stations, psychrometers are generally not suitable for routine monitoring programs. However, they can be used as secondary standards in audit procedures.

Hygrometers are a class of instruments that measure the physical effect that moisture has on a substances, such as hair. For example, the lithium chloride hygrometer uses a probe impregnated with lithium chloride solution. Voltage is supplied to the electrodes in the probe until an equilibrium temperature is reached based on the conductivity of the lithium chloride. The dew point hygrometer, uses a cooled mirror as a sensor; in this case, the temperature of the mirror is monitored to determine the temperature at which dew (or frost) first appears. Such condensation typically disrupts the path of a light beam reflecting off of the cooled surface, causing it to be heated until the condensation disappears. Once the condensation is gone, the surface is cooled again until condensation forms. These oscillating heating and cooling cycles define an average dew point temperature. The temperature of the surface is typically measured by a linear thermistor or a platinum RTD. The thin film capacitor hygrometer measures humidity by detecting the change in capacitance of a thin polymer film; this sensor has a relatively fast response compared to other types of hygrometers.

If possible, humidity sensors should be housed in the same aspirated radiation shield as the temperature sensor. The humidity sensor should be protected from contaminants such as salt, hydrocarbons, and other particulates. The best protection is the use of a porous membrane filter which allows the passage of ambient air and water vapor while keeping out particulate matter.

2.5   Precipitation

Precipitation data, although primarily used in wet deposition modeling, are also used for consistency checks in data review and validation. The two main classes of precipitation measuring devices suitable for meteorological programs are the tipping bucket rain gauge and the weighing rain gauge. Both types of gauge measure total liquid precipitation. Both types of gauge may also be used to measure the precipitation rate, but the tipping bucket is preferable for that application. A third type, the optical rain gauge, has not yet been adequately developed for widespread use.

The tipping bucket rain gauge is probably the most common type of instrument in use for meteorological programs. The rainfall is collected by a cylinder, usually about 8 to 12 inches in diameter, and funneled to one of two small "buckets" on a fulcrum. Each bucket is designed to collect the equivalent of 0.01 inches (0.3 mm) of precipitation, then tip to empty its contents and bring the other bucket into position under the funnel. Each tip of the bucket closes an electrical contact which sends a signal to a signal conditioner for analog and/or digital recording. These are fairly reliable and accurate instruments. Measurement errors may occur if the funnel is too close to the top of the cylinder, resulting in an underestimate of precipitation due to water splashing out of the cylinder, especially during heavy rainfall. Underestimates may also occur during heavy rainfall because precipitation is lost during the tipping action. Inaccuracies may also result if the tipping bucket assembly or the entire gauge is not leveled properly when installed. Tipping buckets are generally equipped with heaters to melt the snow in cold climates, however, the total precipitation may be underestimated due to evaporation of the frozen precipitation caused by the heating element. It would be preferable for the heater to be thermostatically controlled, rather than operate continuously, to avoid underestimation due to evaporation that may also occur during periods of light rain or drizzle. Underestimation of precipitation, especially snowfall, may also result from cases where the gauge is not adequately sheltered from the influence of the wind. A wind shield should therefore be used in climates that experience snowfall. Strong winds can also cause the buckets to tip, resulting in spurious readings.

The weighing rain gauge has the advantage that all forms of precipitation are weighed and recorded as soon as they fall into the gauge. No heater is needed to melt the snow, except to prevent snow and ice buildup on the rim of the gauge, alleviating the problem of evaporation of snow found with the heated tipping bucket gauge. Antifreeze is often used to melt the snow in the bucket. However, the weighing gauge requires more frequent tending than the tipping bucket gauge, and is more sensitive to strong winds causing spurious readings. The weight of precipitation is recorded on a chart mounted on a clock-driven drum for later data reduction. Weighing systems are also available which provide an electrical signal for digital processing.

2.6   Pressure

Atmospheric or barometric pressure can provide information to the meteorologist responsible for reviewing data that may be useful in evaluating data trends, and is also used in

conjunction with air quality measurements. There are two basic types of instruments available for measuring atmospheric pressure, the mercury barometer and the aneroid 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.

Another common type of pressure instrument is the aneroid barometer which consists of two circular disks bounding an evacuated volume. As the pressure changes, the disks flex, 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. Metallic 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 **[5]**.

2.7   Radiation

Solar and/or net radiation data are used to determine atmospheric stability (Section 6.4.2), for calculating various surface-layer parameters used in dispersion modeling (Section 6.6), for estimating convective (daytime) mixing heights, and for modeling photochemical reactions.

Solar radiation refers to the electromagnetic energy in the solar spectrum (0.10 to 4.0 µm wavelength); the latter is commonly classified as ultraviolet (0.10 to 0.40 µm), visible light (0.40 to 0.73 µm), and near-infrared (0.73 to 4.0 µm) radiation. Net radiation includes both solar radiation (also referred to as short-wave radiation) and terrestrial or long-wave radiation; the sign of the net radiation indicates the direction of the flux (a negative value indicates a net upward flux of energy).

Pyranometers are a class of instruments used for measuring energy fluxes in the solar spectrum. These instruments are configured to measure what is referred to as global solar radiation; i.e., direct plus diffuse (scattered) solar radiation incidence on a horizontal surface. The sensing element of the typical pyranometer is protected by a clear glass dome which both protects the sensing element, and functions as a filter preventing entry of energy outside the solar spectrum (i.e., long-wave radiation). The glass domes used on typical pyranometers are transparent to wavelengths in the range of 0.28 to 2.8 µm. Filters can be used instead of the clear glass dome to measure radiation in different spectral intervals; e.g., ultraviolet radiation.

WMO specifications for several classes of pyranometers are given in Table 2-1 **[9]**. First class and secondary standard pyranometers typically employ a thermopile for the sensing element. The thermopile consists of a series of thermojunction pairs, an optically black primary junction, and an optically white reference junction (in some pyranometers, the reference

thermojunction is embedded in the body of the instrument). The temperature difference between the primary and reference junctions which results when the pyranometer is operating generates an electrical potential proportional to the solar radiation. Second class pyranometers typically employ photo-cells for the sensing element. Though less costly than other types of pyranometers, the spectral response of the photovoltaic pyranometer is limited to the visible spectrum.

First class or second class pyranometers should normally be used for measuring global solar radiation, depending on the application. If the solar radiation data are to be used in procedures for estimating stability (Section 6.4) then second class (photovoltaic) pyranometers are acceptable. For most other applications, first class or secondary standard pyranometers should be used. Applications requiring ultraviolet (UV) radiation data should not employ photovoltaic measurements as these instruments are not sensitive to UV radiation.

Table 2-1

Classification of Pyranometers [9]

Characteristic	Units	Secondary Standard	First Class	Second Class
Resolution	$W\ m^{-2}$	±1	±5	±10
Stability	%FS[*]	±1	±2	±5
Cosine Response	%	< ±3	< ±7	< ±15
Azimuth Response	%	< ±3	< ±5	< ±10
Temperature Response	%	±1	±2	±5
Nonlinearity	%FS[*]	±0.5	±2	±5
Spectral Sensitivity	%	±2	±5	±10
Response Time (99%)	seconds	< 25	< 60	< 240

[*] Percent of full scale

2.8   Recommendations

Light weight three cup anemometers (Section 2.1.1) or propeller anemometers (Section 2.1.2) should be used for measuring wind speed. Sensors with high accuracy at low wind speeds and a low starting threshold should be used (see Section 5). Light weight, low friction systems which meet the performance specifications given in Section 5.0 should be used. Heaters should be employed to protect against icing in cold climates. Sonic anenometers and hot wire

anenometers may be used with the approval of the reviewing authority. These instruments are especially suited for use in direct measurements of turbulence.

Wind direction should be measured directly using a wind vane (Section 2.2.1) or may be derived from measurements of wind speed components (Section 2.2.2). Light weight, low friction systems which meet the performance specifications given in Section 5.0 should be used. Heaters should be employed to protect against icing in cold climates. Bivanes are regarded as research grade instruments and are not generally suited for routine monitoring. Data from bivanes may be used on a case by case basis with the approval of the reviewing authority.

Temperature and temperature difference should be measured using resistance temperature devices which meet the performance specifications of Section 5.0. Thermoelectric sensors (thermocouples) are not recommended because of their limited accuracy and complex circuitry.

Humidity should be measured using a dew point, lithium chloride, or thin-film capacitor hygrometer. The hygrometer should meets the performance specifications in Section 5.0.

Precipitation should be measured with a weighing or tipping bucket rain gauge. In cold climates, the gauge should be equipped with a heater and a wind shield.

Atmospheric pressure should be measured with an aneroid barometer which meets the performance specifications given in Section 5.0

First class or second class pyranometers should normally be used for measuring global solar radiation, depending on the application. If the solar radiation data are to be used in procedures for estimating stability (Section 6.4) then second class (photovoltaic) pyranometers are acceptable. For most other applications, first class or secondary standard pyranometers should be used. Applications requiring ultraviolet (UV) radiation data should not employ photovoltaic measurements as these instruments are not sensitive to UV radiation.

Recommended performance specifications for the primary meteorological variables are provided in Table 5-1.

3. SITING AND EXPOSURE

This section provides guidance on siting and exposure of meteorological towers and sensors for the in situ measurement of the primary meteorological variables. Specific guidance is provided for siting in simple terrain (Section 3.2), in complex terrain (Section 3.3), in coastal locations (Section 3.4), and in urban locations (Section 3.5). The issue of representativness is addressed in Section 3.1.

As a general rule, meteorological sensors should be sited at a distance which is beyond the influence of obstructions such as buildings and trees; this distance depends upon the variable being measured as well as the type of obstruction. The other general rule is that the measurements should be representative of meteorological conditions in the area of interest; the latter depends on the application. Secondary considerations such as accessibility and security must be taken into account, but should not be allowed to compromise the quality of the data. In addition to routine quality assurance activities (see Section 8), annual site inspections should be made to verify the siting and exposure of the sensors. Approval for a particular site selection should be obtained from the permit granting agency prior to any site preparation activities or installation of any equipment.

3.1   Representativeness

One of the most important decisions in preparing for an air quality modeling analysis involves the selection of the meteorological data base; this is the case whether one is selecting a site for monitoring, or selecting an existing data base.   These decisions almost always lead to similar questions: "Is the site (are the data) representative?" Examples eliciting a negative response abound; e.g., meteorological data collected at a coastal location affected by a land/sea breeze circulation would generally not be appropriate for modeling air quality at an inland site located beyond the penetration of the sea breeze. One would hope that such examples could be used in formulating objective criteria for use in evaluating representativeness in general. Though this remains a possibility, it is not a straight forward task - this is due in part to the fact that representativeness is an exact condition; a meteorological observation, data base, or monitoring site, either is, or is not representative within the context of whatever criteria are prescribed. It follows that, a quantitative method does not exist for determining representativeness absolutely. Given the above, it should not be surprising that there are no generally accepted analytical or statistical techniques to determine representativeness of meteorological data or monitoring sites.

3.1.1   Objectives for Siting

Representativeness has been defined as "the extent to which a set of measurements taken in a space-time domain reflects the actual conditions in the same or different space-time domain taken on a scale appropriate for a specific application" **[10]**. The space-time and application aspects of the definition as relates to site selection are discussed in the following.

In general, for use in air quality modeling applications, meteorological data should be representative of conditions affecting the transport and dispersion of pollutants in the "area of interest" as determined by the locations of the sources and receptors being modeled. In many instances, e.g. in complex terrain, multiple monitoring sites may be required to adequately represent spatial variations in meteorological conditions affecting transport and/or dispersion.

In steady-state modeling applications, one typically focuses on the meteorological conditions at the release height of the source or sources, or the plume height in the case of buoyant sources. Representativeness for steady-state modeling applications must necessarily be assessed in concert with the steady-state assumption that meteorological conditions are constant within the space-time domain of the application; as typically applied, measurements for a single location, somewhere near the source, are assumed to apply, without change, at all points in the modeling domain. Consistency would call for site selection criteria consistent with the steady-state assumption; i.e., to the extent possible, sites should perhaps be selected such that factors which cause spatial variations in meteorological conditions, are invariant over the spatial domain of the application, whatever that might be. Such factors would include surface characteristics such as ground cover, surface roughness, the presence or absence of water bodies, etc. Similarly, the representativeness of existing third-party data bases should be judged, in part, by comparing the surface characteristics in the vicinity of the meteorological monitoring site with the surface characteristics that generally describe the analysis domain.

Representativeness has an entirely different interpretation for non-steady-state modeling applications which commonly employ three dimensional gridded meteorological fields based on measurements at multiple sites. The meteorological processors which support these applications are designed to appropriately blend available NWS data, local site-specific data, and prognostic mesoscale data; empirical relationships are then used to diagnostically adjust the wind fields for mesoscale and local-scale effects [11], [12] . These diagnostic adjustments can be improved through the use of strategically placed site-specific meteorological observations. Support for such applications is provided to the extent that this guidance can be used for selecting sites to monitor the significant meteorological regimes that may need to be represented in these applications. Site selection for such applications (often more than one location is needed) falls in the category of network design and is beyond the scope of this document. Model user's guides should be consulted for meteorological data requirements and guidance on network design for these applications.

3.1.2   Factors to Consider

Issues of representativeness will always involve case-by-case subjective judgements; consequently, experts knowledgeable in meteorological monitoring and air quality modeling should be included in the site selection process. The following information is provided for consideration in such decisions. Readers are referred to a 1982 workshop report [10] on representativeness for further information on this topic.

- It is important to recognize that, although certain meteorological variables may be considered unrepresentative of another site (for instance, wind direction or wind speed), other variables may be representative (such as temperature, dew point, cloud cover). Exclusion of one variable does not necessarily exclude all. For instance, one can argue that weather observations made at different locations are likely to be similar if the observers at each location are within sight of one another - a stronger argument can be made for some types of observations (e.g., cloud cover) than others. Although, by no means a sufficient condition, the fact that two observers can "see" one another supports a conclusion that they would observe similar weather conditions.

- In general, the representativeness of the meteorological data used in an air quality modeling analysis is dependent on the proximity of the meteorological monitoring site to the "area-of-interest".

- Spatial representativeness of the data will almost always be adversely affected (degraded) by increasing the distance between the sources and receptors (increasing the size of the area-of-interest).

- Although proximity of the meteorological monitoring site is an important factor, representativeness is not simply a function of distance. In some instances, even though meteorological data are acquired at the location of the pollutant source, they may not correctly characterize the important atmospheric dispersion conditions; e.g., dispersion conditions affecting sources located on the coast are strongly affected by off-shore air/sea boundary conditions - data collected at the source would not always reflect these conditions.

- Representativeness is a function of the height of the measurement. For example, one can expect more site-to-site variability in measurements taken close to the surface compared to measurements taken aloft. As a consequence, upper-air measurements are generally representative of much larger spatial domains then are surface measurements.

- Where appropriate, data representativeness should be viewed in terms of the appropriateness of the data for constructing realistic boundary layer profiles and three dimensional meteorological fields.

- Factors that should be considered in selecting a monitoring site in complex terrain include: the aspect ratio and slope of the terrain, the ratios of terrain height to stack height and plume height, the distance of the source from the terrain feature, and the effects of terrain features on meteorological conditions, especially wind speed and wind direction.

3.2   Simple Terrain Locations

For the purposes of this guidance, the term "simple terrain" is intended to mean any site where terrain effects on meteorological measurements are non-significant. The definition of significance depends on the application; for regulatory dispersion modeling applications,

significance is determined by comparing stack-top height to terrain height - terrain which is below stack-top is classified as simple terrain [1]

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3.2.1   Wind Speed and Wind Direction

3.2.1.1 Probe placement

The standard exposure height of wind instruments over level, open terrain is 10 m above the ground [9]. Open terrain is defined as an area where the distance between the instrument and any obstruction is at least ten times the height of that obstruction [2, 4, 9]. The slope of the terrain in the vicinity of the site should be taken into account when determining the relative height of the obstruction [2]. An obstruction may be man-made (such as a building or stack) or natural (such as a hill or a tree). The sensor height, its height above obstructions, and the height/character of nearby obstructions should be documented. Where such an exposure cannot be obtained, the anemometer should be installed at such a height that it is reasonably unaffected by local obstructions and represents the approximate wind values that would occur at 10 m in the absence of the obstructions. This height, which depends on the extent, height, and distance of obstructions and on site availability, should be determined on a case-by-case basis. Additional guidance on the evaluation of vertical profiles (Section 6.1.3) and surface roughness (Section 6.4.2) may be helpful in determining the appropriate height.

If the source emission point is substantially above 10 m, then additional wind measurements should be made at stack top or 100 m, whichever is lower [1]. In cases with stack heights of 200 m or above, the appropriate measurement height should be determined by the Regional Office on a case-by-case basis. Because maximum practical tower heights are on the order of 100 m, wind data at heights greater than 100 m will most likely be determined by some other means. Elevated wind measurements can be obtained via remote sensing (see Section 9.0). Indirect values can be estimated by using a logarithmic wind-speed profile relationship. For this purpose, instruments should be located at multiple heights (at least three) so that site-specific wind profiles can be developed.

3.2.1.2 Obstructions

Buildings. Aerodynamic effects due to buildings and other major structures, such as cooling towers, should be avoided to the extent possible in the siting of wind sensors; such effects are significant, not only in the vicinity of the structures themselves, but at considerable distances downwind. Procedures for assessing aerodynamic effects have been developed from observing such effects in wind tunnels [13], [14]. Wind sensors should only be located on building rooftops as a last resort; in such cases, the sensors should be located at a sufficient height above the rooftop to avoid the aerodynamic wake. This height can be determined from on-site measurements (e.g., smoke releases) or wind tunnel studies. As a rule of thumb, the total depth of the building wake is estimated to be approximately 2.5 times the height of the building [1].

Trees. In addition to the general rules concerning obstructions noted above, additional considerations may be important for vegetative features (e.g., growth rates). Seasonal effects should also be considered for sites near deciduous trees. For dense, continuous forests where an open exposure cannot be obtained, measurements should be taken at 10m above the height of the general vegetative canopy.

Towers. Sensors mounted on towers are frequently used to collect wind speed measurements at more than one height. To avoid the influence of the structure itself, closed towers, stacks, cooling towers, and similar solid structures should not be used to support wind instruments. Open-lattice towers are preferred. Towers should be located at or close to plant elevation in an open area representative of the area of interest.

Wind instruments should be mounted on booms at a distance of at least twice the diameter/diagonal of the tower (from the nearest point on the tower) into the prevailing wind direction or wind direction of interest **[2]**. Where the wind distribution is strongly bimodal from opposite directions, such as in the case of up-valley and down-valley flows, then the booms should be at right angles to the predominant wind directions. The booms must be strong enough so that they will not sway or vibrate sufficiently to influence standard deviation values in strong winds. Folding or collapsible towers are not recommended since they may not provide sufficient support to prevent such vibrations, and also may not be rigid enough to ensure proper instrument orientation. The wind sensors should be located at heights of minimum tower density (i.e., minimum number of diagonal cross-members) and above/below horizontal cross-members **[2]**. Since practical considerations may limit the maximum boom length, wind sensors on large towers (e.g., TV towers and fire look-out towers) may only provide accurate measurements over a certain arc. In such cases, two systems on opposite sides of the tower may be needed to provide accurate measurements over the entire 360°. If such a dual system is used, the method of switching from one system to the other should be carefully specified. A wind instrument mounted on top of a tower should be mounted at least one tower diameter/diagonal above the top of the tower structure.

Surface roughness. The surface roughness over a given area reflects man-made and natural obstructions, and general surface features. These roughness elements effect the horizontal and vertical wind patterns. Differences in the surface roughness over the area of interest can create differences in the wind pattern that may necessitate additional measurement sites. A method of estimating surface roughness length, z_o, is presented in Section 6.4.2. If an area has a surface roughness length greater than 0.5 m, then there may be a need for special siting considerations (see discussion in Sections 3.3 and 3.5).

3.2.1.3 Siting considerations

A single well-located measurement site can be used to provide representative wind measurements for non-coastal, flat terrain, rural situations. Wind instruments should be placed taking into account the purpose of the measurements. The instruments should be located over level, open terrain at a height of 10 m above the ground, and at a distance of at least ten times the

height of any nearby obstruction. For elevated releases, additional measurements should be made at stack top or 100 m, whichever is lower **[1]**. In cases with stack heights of 200 m or above, the appropriate measurement height should be determined by the Regional Office on a case-by-case basis.

3.2.2 Temperature, Temperature Difference, and Humidity

The siting and exposure criteria for temperature, temperature difference and humidity are similar. Consequently, these variables are discussed as a group in the following; exceptions are noted as necessary.

3.2.2.1 Probe placement

Ambient temperature and humidity should be measured at 2 m, consistent with the World Meteorological Organization (WMO) standards for ambient measurements **[9]**. Probe placement for temperature difference measurements depend on the application.. For use in estimating surface layer scaling parameters (Section 6.6.4), the temperature difference should be measured between $20z_0$ and $100z_0$; the same recommendation applies to temperature difference measurements for use in estimating the P-G stability category using the solar radiation delta-T method (Section 6.4.4.2). For use in estimating stable plume rise, temperature difference measurements should be made across the plume rise layer, a minimum separation of 50 m is recommended. For sites that experience large amounts of snow, adjustments to the temperature measurement height may be necessary, however, the ambient temperature measurement should not extend above 10 m. For analysis of cooling tower impacts, measurements of temperature and humidity should also be obtained at source height and within the range of final plume height. The measurement of temperature difference for analysis of critical dividing streamline height, H_{crit}, a parameter used in complex terrain modeling, is discussed in Section 3.3.3.

Temperature and humidity sensors should be located over an open, level area at least 9 m in diameter. The surface should be covered by short grass, or, where grass does not grow, the natural earth surface **[2, 9]**. Instruments should be protected from thermal radiation (from the earth, sun, sky, and any surrounding objects) and adequately ventilated using aspirated shields. Forced aspiration velocity should exceed 3 m/s, except for lithium chloride dew cells which operate best in still air **[2]**. If louvered shelters are used instead for protection (at ground level only), then they should be oriented with the door facing north (in the Northern Hemisphere). Temperature and humidity data obtained from naturally-ventilated shelters will be subject to large errors when wind speeds are light (less than about 3 m/s).

Temperature and humidity sensors on towers should be mounted on booms at a distance of about one diameter/diagonal of the tower (from the nearest point on the tower) **[2]**. In this case, downward facing aspiration shields are necessary.

3.2.2.2 Obstructions

Temperature and humidity sensors should be located at a distance of at least four times the height of any nearby obstruction and at least 30 m from large paved areas [2], [15]. Other situations to avoid include: large industrial heat sources, rooftops, steep slopes, sheltered hollows, high vegetation, shaded areas, swamps, areas where frequent snow drifts occur, low places that hold standing water after rains, and the vicinity of air exhausts (e.g., from a tunnel or subway) [2, 9].

3.2.2.3 Siting considerations

In siting temperature sensors, care must be taken to preserve the characteristics of the local environment, especially the surface. Protection from thermal radiation (with aspirated radiation shields) and significant heat sources and sinks is critical. Siting recommendations are similar for humidity measurements, which may be used for modeling input in situations involving moist releases, such as cooling towers. For temperature difference measurements, sensors should be housed in identical aspirated radiation shields with equal exposure.

3.2.3   Precipitation

3.2.3.1 Probe placement

A rain gauge should be sited on level ground so the mouth is horizontal and open to the sky [2]. The underlying surface should be covered with short grass or gravel. The height of the opening should be as low as possible (minimum: 30 cm), but should be high enough to avoid splashing in from the ground.

Rain gauges mounted on towers should be located above the average level of snow accumulation [15]. In addition, collectors should be heated if necessary to properly measure frozen precipitation [4].

3.2.3.2 Obstructions

Nearby obstructions can create adverse effects on precipitation measurements (e.g., funneling, reflection, and turbulence) which should be avoided. On the other hand, precipitation measurements may be highly sensitive to wind speed, especially where snowfall contributes a significant fraction of the total annual precipitation. Thus, some sheltering is desirable. The need to balance these two opposite effects requires some subjective judgment.

The best exposure may be found in orchards, openings in a grove of trees, bushes, or shrubbery, or where fences or other objects act together to serve as an effective wind-break. As a general rule, in sheltered areas where the height of the objects and their distance to the instrument is uniform, their height (above the instrument) should not exceed twice the distance (from the instrument) [15]. In open areas, the distance to obstructions should be at least two, and

preferably four, times the height of the obstruction. It is also desirable in open areas which experience significant snowfall to use wind shields such as those used by the National Weather Service **[2, 9, 15]**.

3.2.3.3 Siting considerations

In view of the sensitivity to wind speed, every effort should be made to minimize the wind speed at the mouth opening of a precipitation gauge. This can be done by using wind shields. Where snow is not expected to occur in significant amounts or with significant frequency, use of wind shields is less important. However, the catch of either frozen or liquid precipitation is influenced by turbulent flow at the collector, and this can be minimized by the use of a wind shield.

3.2.4   Pressure

Although atmospheric pressure may be used in some modeling applications, it is not a required input variable for steady-state modeling applications. Moreover, the standard atmospheric pressure for the station elevation may often be sufficient for those applications which require station pressure; the model user's guide should be checked for specific model requirements.

3.2.5   Radiation

3.2.5.1 Probe placement

Pyranometers used for measuring incoming (solar) radiation should be located with an unrestricted view of the sky in all directions during all seasons, with the lowest solar elevation angle possible. Sensor height is not critical for pyranometers. A tall platform or rooftop is a desirable location **[2]**. Net radiometers should be mounted about 1 m above the ground **[2]**.

3.2.5.2 Obstructions

Pyranometers should be located to avoid obstructions casting a shadow on the sensor at any time. Also, light colored walls and artificial sources of radiation should be avoided **[2]**. Net radiometers should also be located to avoid obstructions to the field of view both upward and downward **[2]**.

3.2.5.3 Siting considerations

Solar radiation measurements should be taken in open areas free of obstructions. The ground cover under a net radiometer should be representative of the general site area. The given application will govern the collection of solar or net radiation data.

3.3   Complex Terrain Locations

For the purposes of this guidance, the term "complex terrain" is intended to mean any site where terrain effects on meteorological measurements may be significant. Terrain effects include aerodynamic wakes, density-driven slope flows, channeling, flow accelerations over the crest of terrain features, etc.; these flows primarily affect wind speed and wind direction measurements, however, temperature and humidity measurements may also be affected. The definition of significance depends on the application; for regulatory dispersion modeling applications, significance is determined by comparing stack-top height and/or an estimated plume height to terrain height - terrain which is below stack-top is classified as simple terrain (see Section 3.2), terrain between stack-top height and plume height is classified as intermediate terrain, and terrain which is above plume height is classified as complex terrain **[1]**.

Vertical gradients and/or discontinuities in the vertical profiles of meteorological variables are often significant in complex terrain. Consequently, measurements of the meteorological variables affecting transport and dispersion of a plume (wind direction, wind speed, and σ_θ) should be made at multiple levels in order to ensure that data used for modeling are representative of conditions at plume level. The ideal arrangement in complex terrain involves siting a tall tower between the source and the terrain feature of concern. The tower should be tall enough to provide measurements at plume level. Other terrain in the area should not significantly affect plume transport in a different manner than that measured by the tower. Since there are not many situations where this ideal can be achieved, a siting decision in complex terrain will almost always be a compromise. Monitoring options in complex terrain range from a single tall tower to multiple tall towers supplemented by data from one or more remote sensing platforms. Other components of the siting decision include determining tower locations, deciding whether or not a tower should be sited on a nearby terrain feature, and determining levels (heights) for monitoring. Careful planning is essential in any siting decision. Since each complex terrain situation has unique features to consider, no specific recommendations can be given to cover all cases. However, the siting process should be essentially the same in all complex terrain situations. Recommended steps in the siting process are as follows:

- Define the variables that are needed for a particular application.

- Develop as much information as possible to define what terrain influences are likely to be important. This should include examination of topographic maps of the area with terrain above physical stack height outlined. Preliminary estimates of plume rise should be made to determine a range of expected plume heights. If any site specific meteorological data are available, they should be analyzed to see what can be learned about the specific

terrain effects on air flow patterns. An evaluation by a meteorologist based on a site visit would also be desirable.

- Examine alternative measurement locations and techniques for required variables. Advantages and disadvantages of each technique/location should be considered, utilizing as a starting point the discussions presented above and elsewhere in this document.

- Optimize network design by balancing advantages and disadvantages.

It is particularly important in complex terrain to consider the end use of each variable separately. Guidance and concerns specific to the measurement of wind speed, wind direction, and temperature difference in complex terrain are discussed in the following sections.

3.3.1   Wind Speed

For use in plume rise calculations, wind speed should be measured at stack top or 100 m, whichever is lower. Ideally, the wind speed sensor should be mounted on a tower located near stack base elevation; however, a tower located on nearby elevated terrain may be used in some circumstances. In this latter case, the higher the tower above terrain the better (i.e. less compression effect); a 10-meter tower generally will not be sufficient. The measurement location should be evaluated for representativeness of both the dilution process and plume rise.

Great care should be taken to ensure that the tower is not sheltered in a closed valley (this would tend to over-estimate the occurrence of stable conditions) or placed in a location that is subject to streamline compression effects (this would tend to underestimate the occurrence of stable conditions). It is not possible to completely avoid both of these concerns. If a single suitable location cannot be found, then alternative approaches, such as multiple towers or a single tall tower supplemented by one or more remote sensing platforms should be considered in consultation with the Regional Office.

3.3.2   Wind Direction

The most important consideration in siting a wind direction sensor in complex terrain is that the measured direction should not be biased in a particular direction that is not experienced by the pollutant plume. For example, instruments on a meteorological tower located at the bottom of a well-defined valley may measure directions that are influenced by channeling or density-driven up-slope or down-slope flows. If the pollutant plume will be affected by the same flows, then the tower site is adequate. Even if the tower is as high as the source's stack, however, appreciable plume rise may take the plume out of the valley influence and the tower's measured wind direction may not be appropriate for the source (i.e., biased away from the source's area of critical impact).

The determination of potential bias in a proposed wind direction measurement is not an easy judgement to make. Quite often the situation is complicated by multiple flow regimes, and the existence of bias is not evident. This potential must be considered, however, and a rationale

developed for the choice of measurement location. Research has indicated that a single wind measurement location/site may not be adequate to define plume transport direction in some situations. While the guidance in this document is concerned primarily with means to obtain a single hourly averaged value of each variable, it may be appropriate to utilize more than one measurement of wind direction to calculate an "effective" plume transport direction for each hour.

3.3.3   Temperature Difference

The requirements of a particular application should be used as a guide in determining how to make measurements of vertical temperature difference in complex terrain. Stable plume rise and the critical dividing streamline height (H_{crit}), which separates flow that tends to move around a hill (below H_{crit}) from flow that tends to pass over a hill (above H_{crit}), are both sensitive to the vertical temperature gradient. The height ranges of interest are from stack top to plume height for the former and from plume height to the top of the terrain feature for the latter. The direct measurement of the complete temperature profile is often desirable but not always practical. The following discussion presents several alternatives for measuring the vertical temperature gradient along with some pros and cons.

Tower measurement: A tower measurement of temperature difference can be used as a representation of the temperature profile. The measurement should be taken between two elevated levels on the tower (e.g. 50 and 100 meters) and should meet the specifications for temperature difference discussed in Section 5.0. A separation of 50 m between the two sensors is preferred. The tower itself could be located at stack base elevation or on elevated terrain: optimum location depends on the height of the plume. Both locations may be subject to radiation effects that may not be experienced by the plume if it is significantly higher than the tower.

The vertical extent of the temperature probe may be partially in and partially out of the surface boundary layer, or may in some situations be entirely contained in the surface boundary layer while the plume may be above the surface boundary layer.

Balloon-based temperature measurements: Temperature profiles taken by balloon-based systems can provide the necessary information but are often not practical for developing a long-term data base. One possible use of balloon-based temperature soundings is in developing better "default" values of the potential temperature gradient on a site-specific basis. A possible approach would be to schedule several periods of intensive soundings during the course of a year and then derive appropriate default values keyed to stability category and wind speed and/or other appropriate variables. The number and scheduling of these intensive periods should be established as part of a sampling protocol.

Deep-layer absolute temperature measurements: If the vertical scale of the situation being modeled is large enough (200 meters or more), it may be acceptable to take the difference between two independent measurements of absolute temperature (i.e., temperature measurements would be taken on two different towers, one at plant site and one on terrain) to serve as a surrogate measurement of the temperature profile. This approach must be justified on a case-by-

case basis, and should be taken only with caution. Its application should be subject to the following limitations:

- Depth of the layer should be 200 meters at a minimum;

- The measurement height on each tower should be at least 60 meters;

- Horizontal separation of the towers should not exceed 2 kilometers;

- No internal boundary layers should be present, such as near shorelines; and

- Temperature profiles developed with the two-tower system should be verified with a program of balloon-based temperature profile measurements.

3.4   Coastal Locations

The unique meteorological conditions associated with local scale land-sea breeze circulations necessitate special considerations. For example, a stably stratified air mass over water can become unstable over land due to changes in roughness and heating encountered during daytime conditions and onshore flow. An unstable thermal internal boundary layer (TIBL) can develop, which can cause rapid downward fumigation of a plume initially released into the stable onshore flow. To provide representative measurements for the entire area of interest, multiple sites would be needed: one site at a shoreline location (to provide 10 m and stack height/plume height wind speed), and additional inland sites perpendicular to the orientation of the shoreline to provide wind speed within the TIBL, and estimates of the TIBL height. Where terrain in the vicinity of the shoreline is complex, measurements at additional locations, such as bluff tops, may also be necessary. Further specific measurement requirements will be dictated by the data input needs of a particular model. A report prepared for the Nuclear Regulatory Commission **[16]** provides a detailed discussion of considerations for conducting meteorological measurement programs at coastal sites.

3.5   Urban Locations

Urban areas are characterized by increased heat flux and surface roughness. These effects, which vary horizontally and vertically within the urban area, alter the wind pattern relative to the outlying rural areas (e.g., average wind speeds are decreased). The close proximity of buildings in downtown urban areas often precludes strict compliance with the previous sensor exposure guidance. For example, it may be necessary to locate instruments on the roof of the tallest available building. In such cases, the measurement height should take into account the proximity of nearby tall buildings and the difference in height between the building (on which the instruments are located) and the other nearby tall buildings.

In general, multiple sites are needed to provide representative measurements in a large urban area. This is especially true for ground-level sources, where low-level, local influences, such as street canyon effects, are important, and for multiple elevated sources scattered over an

urban area. However, due to the limitations of the recommended steady-state guideline models (i.e. they recognize only a single value for each input variable on an hourly basis), and resource and practical constraints, the use of a single site is necessary. At the very least, the single site should be located as close as possible to the source in question.

3.6   Recommendations

Recommendations for siting and exposure of in situ meteorological sensors in simple terrain are as follows:

> *Sensors for wind speed and wind direction should be located over level, open terrain at a height of 10 m above ground level and at a distance at least ten times the height of nearby obstructions. For elevated releases, additional measurements should be made at stack top or 100 m, whichever is lower. Monitoring requirements for stacks 200 m and above should be determined in consultation with the appropriate EPA Regional Office.*

> *Temperature sensors should be located at 2 m. Probe placement for temperature difference measurements depend on the application. For use in estimating surface layer stability, the measurement should be made between $20z_0$ and $100z_0$; the same recommendation applies to temperature difference measurements for use in estimating the P-G stability category using the solar radiation delta-T method. For use in estimating stable plume rise, temperature difference measurements should be made across the plume rise layer, a minimum separation of 50 m is recommended for this application. Temperature sensors should be shielded to protect them from thermal radiation and any significant heat sources or sinks.*

> *Pyranometers used for measuring incoming (solar) radiation should be located with an unrestricted view of the sky in all directions during all seasons. Sensor height is not critical for pyranometers; a tall platform or rooftop is an acceptable location. Net radiometers should be mounted about 1 m above ground level.*

Specific recommendations applicable to siting and exposure of meteorological instruments in complex terrain are not possible. Generally, one should begin the process by conducting a screening analysis to determine, among other things, what terrain features are likely to be important; the screening analysis should also identify potential worse case meteorological conditions. This information should then be used to design a monitoring plan for the specific application.

Special siting considerations also apply to coastal and urban sites. Multiple sites, though often desirable, may not always be possible in these situations. In general, site selection for meteorological monitoring in support of regulatory modeling applications in coastal and urban locations should be conducted in consultation with the appropriate EPA Regional Office.

If the recommendations in this section cannot be achieved, then alternate approaches should be developed in consultation with the appropriate EPA Regional Office. Approval of site

selection for meteorological monitoring should be obtained from the permit granting authority prior to installation of any equipment.

4. METEOROLOGICAL DATA RECORDING

The various meteorological data recording systems available range in complexity from very simple analog or mechanical pulse counter systems to very complex multichannel, automated, microprocessor-based digital data acquisition systems. The function of these systems is to process the electrical output signals from various sensors/transducers and convert them into a form that is usable for display and subsequent analysis. The sensor outputs may come in the form of electrical DC voltages, currents of varying amperage, and/or frequency-varying AC voltages.

4.1   Signal Conditioning

The simpler analog systems utilize the electrical output from a transducer to directly drive the varying pen position on a strip chart. For some variables, such as wind run (total passage of wind) and precipitation, the transducer may produce a binary voltage (either "on" or "off") which is translated into an event mark on the strip chart. Many analog systems and virtually all digital systems require a signal conditioner to translate the transducer output into a form that is suitable for the remainder of the data acquisition system. This translation may include amplifying the signal, buffering the signal (which in effect isolates the transducer from the data acquisition system), or converting a current (amperage) signal into a voltage signal.

4.2   Recording Mechanisms

Both analog and digital systems have a variety of data recording mechanisms or devices available. Analog data may be recorded as continuous traces on a strip chart or as event marks on a chart, as previously described, or as discrete samples on a multi point recorder. The multi point recorder will generally sample each of several variables once every several seconds. The traces for the different variables are differentiated by different colors of ink or by channel numbers printed on the chart next to the trace, or by both. The data collected by digital data acquisition systems may be recorded in hard copy form by a printer or terminal either automatically or upon request, and are generally also recorded on some machine-readable medium such as a magnetic disk storage or tape storage device or a solid-state (nonmagnetic) memory cartridge. Digital systems have several advantages over analog systems in terms of the speed and accuracy of handling the data, and are therefore preferred as the primary recording system. Analog systems may still be useful as a backup to minimize the potential for data loss. For wind speed and wind direction, the analog strip chart records can also provide valuable information to the person responsible for evaluating the data..

4.3   Analog-to-Digital Conversion

A key component of any digital data acquisition system is the analog-to-digital (A/D) converter. The A/D converter translates the analog electrical signal into a binary form that is

suitable for subsequent processing by digital equipment. In most digital data acquisition systems a single A/D converter is used for several data channels through the use of a multiplexer. The rate at which the multiplexer channel switches are opened and closed determines the sampling rates for the channels - all channels need not be sampled at the same the frequency.

4.4   Data Communication

Depending on the type of system, there may be several data communication links. Typically the output signals from the transducers are transmitted to the on-site recording devices directly via hardwire cables. For some applications involving remote locations the data transmission may be accomplished via a microwave telemetering system or perhaps via telephone lines with a dial-up or dedicated line modem system.

4.5   Sampling Rates

The recommended sampling rate for a digital data acquisition system depends on the end use of the data. Substantial evidence and experience suggest that 360 data values evenly spaced during the sampling interval will provide estimates of the standard deviation to within 5 or 10% **[3]**. Estimates of the mean should be based on at least 60 samples to obtain a similar level of accuracy. Sometimes fewer samples will perform as well, but no general guide can be given for identifying these cases before sampling; in some cases, more frequent sampling may be required. If single-pass processing (as described in Section 6.2.1) is used to compute the mean scalar wind direction, then the output from the wind direction sensor (wind vane) should be sampled at least once per second to insure that consecutive values do not differ by more than 180 degrees.

The sampling rate for multi point analog recorders should be at least once per minute. Chart speeds should be selected to permit adequate resolution of the data to achieve the system accuracies recommended in Section 5.1. The recommended sampling rates are minimum values; the accuracy of the data will generally be improved by increasing the sampling rate.

4.6   Recommendations

A microprocessor-based digital data acquisition system should be used as the primary data recording system; analog data recording systems may be used as a backup. Wind speed and wind direction analog recording systems should employ continuous-trace strip-charts; other variables may be recorded on multi point charts. The analog charts used for backup should provide adequate resolution to achieve the system accuracies recommended in Section 5.1.

Estimates of means should be based on at least 60 samples (one sample per minute for an hourly mean). Estimates of the variance should be based on at least 360 samples (six samples per minute for an hourly variance). If single-pass processing is used to calculate the mean scalar wind direction then the output from the wind vane should be sampled at least once per second.

5. SYSTEM PERFORMANCE

5.1   System Accuracies

Accuracy is the amount by which a measured variable deviates from a value accepted as true or standard. Accuracy can be thought of in terms of individual component accuracy or overall system accuracy. For example, the overall accuracy of a wind speed measurement system includes the individual component accuracies of the cup or propeller anemometer, signal conditioner, analog-to-digital converter, and data recorder.

The accuracy of a measurement system can be estimated if the accuracies of the individual components are known. The system accuracy would be the square root of the sum of the squares of the random component accuracies [17]. The accuracies recommended for meteorological monitoring systems are listed in Table 5-1. These are stated in terms of overall system accuracies, since it is the data from the measurement system which are used in air quality modeling analyses. Recommended measurement resolutions, i.e., the smallest increments that can be distinguished, are also provided in Table 5-1. These resolutions are considered necessary to maintain the recommended accuracies, and are also required in the case of wind speed and wind direction for computations of standard deviations.

Table 5-1

Recommended System Accuracies and Resolutions

Meteorological Variable	System Accuracy	Measurement Resolution
Wind Speed (horizontal and vertical)	± (0.2 m/s + 5% of observed)	0.1 m/s
Wind Direction (azimuth and elevation)	± 5 degrees	1.0 degree
Ambient Temperature	± 0.5 °C	0.1 °C
Vertical Temperature Difference	± 0.1 °C	0.02 °C
Dew Point Temperature	± 1.5 °C	0.1 °C
Precipitation	± 10% of observed or ± 0.5 mm	0.3 mm
Pressure	± 3 mb (0.3 kPa)	0.5 mb
Solar Radiation	± 5% of observed	10 W/m^2

The recommendations provided in Table 5-1 are applicable to microprocessor-based digital systems (the primary measurement system). For analog systems, used as backup, these recommendations may be relaxed by 50 percent. The averaging times associated with the recommended accuracies correspond to the averaging times associated with the end use of the data (nominally, 1-hour averaging for regulatory modeling applications) and with the audit methods recommended to evaluate system accuracies.

5.2   Response Characteristics of Meteorological Sensors

The response characteristics of the sensors used in meteorological monitoring must be known to ensure that data are appropriate for the intended application. For example, an anemometer designed to endure the rigors experienced on an ocean buoy would not be suitable for monitoring fine scale turbulence in a wind tunnel; the latter application requires a more sensitive instrument with a faster response time (e.g., a sonic anemometer). On the other hand, a sonic anemometer is probably unnecessary if the data are to be used only to calculate hourly averages for use in a dispersion model. Recommended response characteristics for meteorological sensors used in support of air quality dispersion modeling are given in Table 5-2. Definitions of terms commonly associated with instrument response characteristics (including the terms used in Table 5-2) are provided in the following.

Calm. Any average wind speed below the starting threshold of the wind speed or direction sensor, whichever is greater **[4]**.

Damping ratio. The motion of a vane is a damped oscillation and the ratio in which the amplitude of successive swings decreases is independent of wind speed. The damping ratio, h, is the ratio of actual damping to critical damping. If a vane is critically damped, h=l and there is no overshoot in response to sudden changes in wind direction **[18] [19] [20]**.

Delay distance. The length of a column of air that passes a wind vane such that the vane will respond to 50% of a sudden angular change in wind direction **[19]** The delay distance is commonly specified as "50% recovery" using "10° displacement" **[2, 3]**.

Distance constant. The distance constant of a sensor is the length of fluid flow past the sensor required to cause it to respond to 63.2%, i.e., l - l/e, of the increasing step-function change in speed **[19,20]**. Distance constant is a characteristic of cup and propeller (rotational) anemometers.

Range. This is a general term which usually identifies the limits of operation of a sensor, most often within which the accuracy is specified.

Threshold (starting speed). The wind speed at which an anemometer or vane first starts to perform within its specifications20.

Time constant. The time constant is the period that is required for a (temperature) sensor to respond to 63.2%, i.e., l - l/e, of the step-wise change (in temperature). The term is applicable to

any "first-order" sensors, those that respond asymptotically to a step change in the variable being measured, e.g., temperature, pressure, etc.

Table 5-2

Recommended Response Characteristics for Meteorological Sensors

Meteorological Variable	Sensor Specification(s)	
Wind Speed		
Horizontal	Starting Speed:	≤ 0.5 m/s
	Distance Constant:	≤ 5 m
Vertical	Starting Speed:	≤ 0.25 m/s
	Distance Constant:	≤ 5 m
Wind Direction	Starting Speed:	≤ 0.5 m/s @ 10 deg.
	Damping Ratio:	0.4 to 0.7
	Delay Distance:	≤ 5 m
Temperature	Time Constant:	≤ 1 minute
Temperature Difference	Time Constant:	≤ 1 minute
Dew Point Temperature	Time Constant:	≤ 30 minutes
	Range:	-30°C to +30°C
Solar Radiation	Time Constant:	5 sec.
	Operating Range:	-20°C to +40°C
	Spectral Response:	285 nm to 2800 nm

Several publications are available that either contain tabulations of reported sensor response characteristics **[18]**, **[21]** or specify, suggest or recommend values for certain applications **[2, 3, 9]**. Moreover, many manufacturers are now providing this information for the instruments they produce **[21]**. An EPA workshop report on meteorological instrumentation **[3]** expands on these recommendations for certain variables.

Manufacturers of meteorological instruments should provide evidence that the response characteristics of their sensors have been determined according to accepted scientific/technical methods, e.g., ASTM standards **[22]**. Verifying a manufacturer's claims that a meteorological sensor possesses the recommended response characteristics (Table 5-2) is another matter; such verification can accurately be accomplished only in a laboratory setting. In leu of a laboratory test, one must rely on quality assurance performance audit procedures (Section 8.4) - the latter will normally provide assurance of satisfactory performance.

5.3   Data Recovery

5.3.1   Length of Record

The duration of a meteorological monitoring program should be set to ensure that worst-case meteorological conditions are adequately represented in the data base; the minimum duration for most dispersion modeling applications is one year. Recommendations on the length of record for regulatory dispersion modeling as published in The Guideline on Air Quality Models **[1]** are: five years of National Weather Service (NWS) meteorological data or at least one year of site-specific data. Consecutive years from the most recent, readily available 5-year period are preferred.

5.3.2   Completeness Requirement

Regulatory analyses for the short-term ambient air quality standards (1 to 24-hour averaging) involve the sequential application of a dispersion model to every hour in the analysis period (one to five years); such analyses require a meteorological record for every hour in the analysis period. Substitution for missing or invalid data is used to meet this requirement. Applicants in regulatory modeling analyses are allowed to substitute for up to 10 percent of the data; conversely, the meteorological data base must be 90 percent complete (before substitution) in order to be acceptable for use in regulatory dispersion modeling. The following guidance should be followed for purposes of assessing compliance with the 90 percent completeness requirement:

- Lost data due to calibrations or other quality assurance procedures is considered missing data.

- A variable is not considered missing if data for a backup, collocated sensor is available.

- A variable is not considered missing if backup data from an analog system; which meets the applicable response, accuracy and resolution criteria; are available.

- Site specific measurements for use in stability classification are considered equivalent such that the 90 percent requirement applies to stability and not to the measurements (e.g., σ_E and σ_A) used for estimating stability.

- The 90 percent requirement applies on a quarterly basis such that 4 consecutive quarters with 90 percent recovery are required for an acceptable one-year data base.

- The 90 percent requirement applies to each of the variables wind direction, wind speed, stability, and temperature and to the joint recovery of wind direction, wind speed, and stability.

Obtaining the 90 percent goal will necessarily require a commitment to routine preventive maintenance and strict adherence to approved quality assurance procedures (Sections 8.5 and 8.6). Some redundancy in sensors, recorders and data logging systems may also be necessary. With these prerequisites, the 90 percent requirement should be obtainable with available high quality instrumentation. Applicants failing to achieve such are required to continue monitoring until 4 consecutive quarters of acceptable data with 90 percent recovery have been obtained. Substitutions for missing data are allowed, but may not exceed 10 percent of the hours (876 hours per year) in the data base. Substitution procedures are discussed in Section 6.8.

5.4   Recommendations

Recommended system accuracies and resolutions for meteorological data acquisition systems are given in Table 5-l. These requirements apply to the primary measurement system and assume use of a microprocessor digital recording system. If an analog system is used for backup, the values for system accuracy may be relaxed by 50 percent. Recommended response characteristics for meteorological sensors are given in Table 5-2. Manufacturer's documentation verifying an instrument's response characteristics should be reviewed to ensure that verification tests are conducted in a laboratory setting according to accepted scientific/technical methods. Data bases for use in regulatory dispersion modeling applications should be 90 percent complete (before substitution). The 90 percent requirement applies to each meteorological variable separately and to the joint recovery of wind direction, wind speed, and stability. Compliance with the 90 percent requirement should be assessed on a quarterly basis.

6. METEOROLOGICAL DATA PROCESSING

This section provides guidance for processing of meteorological data for use in air quality modeling as follows: Section 6.1 (Averaging and Sampling Strategies), Section 6.2 (Wind Direction, and Wind Speed), Section 6.3 (Temperature), Section 6.4 (Stability), Section 6.5 (Mixing Height), Section 6.6 (Boundary Layer Parameters), Section 6.7 (Use of Airport Data), and Section 6.8 (Treatment of Missing Data). Recommendations are summarized in Section 6.9.

6.1   Averaging and Sampling Strategies

Hourly averaging may be assumed unless stated otherwise; this is in keeping with the averaging time used in most regulatory air quality models. The hourly averaging is associated with the end product of data processing (i.e., the values that are passed on for use in modeling). These hourly averages may be obtained by averaging samples over an entire hour or by averaging a group of shorter period averages. If the hourly average is to be based on shorter period averages, then it is recommended that 15-minute intervals be used. At least two valid 15-minute periods are required to represent the hourly period. The use of shorter period averages in calculating an hourly value has advantages in that it minimizes the effects of meander under light wind conditions in the calculation of the standaard deviation of the wind direction, and it provides more complete information to the meteorologist reviewing the data for periods of transition. It also may allow the recovery of data that might otherwise be lost if only part of the hour is missing.

Sampling strategies vary depending on the variable being measured, the sensor employed, and the accuracy required in the end use of the data. The recommended sampling averaging times for wind speed and wind direction measurements is 1-5 seconds; for temperature and temperature difference measurements, the recommended sample averaging time is 30 seconds **[3]**.

6.2   Wind Direction and Wind Speed

This section provides guidance for processing of in situ measurements of wind direction and wind speed using conventional in situ sensors; i.e., cup and propeller anemometers and wind vanes. Guidance for processing of upper-air wind measurements obtained with remote sensing platforms is provided in Section 9. Recommendations are provided in the following for processing of winds using both scalar computations (Section 6.2.1) and vector computations (Section 6.2.2). Unless indicated otherwise, the methods recommended in Sections 6.2.1 and 6.2.2 employ single-pass processing; these methods facilitate real-time processing of the data as it is collected. Guidance on the treatment of calms is provided in Section 6.2.3.   Processing of data to obtain estimates of turbulence parameters is addressed in Section 6.2.4.   Guidance on the use of a power-law for extrapolating wind speed with height is provided in Section 6.2.5. The notation for this section is defined in Table 6-2.

Table 6-1

Notation Used in Section 6.2

Observed raw data

     u_i signed magnitude of the horizontal component of the wind vector (i.e., the wind speed)

     θ_i azimuth angle of the wind vector, measured clockwise from north (i.e., the wind direction)

     w_i signed magnitude of the vertical component of the wind vector

     ϕ_i elevation angle of the wind vector (bivane measurement)

     N the number of valid observations

Scalar wind computations

     $\overline{u}, \overline{U}$ scalar mean wind speed

     $\overline{u}_h$ harmonic mean wind speed

     $\overline{\theta}$ mean azimuth angle of the wind vector (i.e. the mean wind direction)

     $\overline{w}$ mean value of the vertical component of the wind speed

     $\overline{\phi}$ mean elevation angle of the wind vector

     σ_u standard deviation of the horizontal component of the wind speed

     σ_A, σ_θ standard deviation of the azimuth angle of the wind

     σ_w standard deviation of the vertical component of the wind speed

     σ_E, σ_ϕ standard deviation of the elevation angle of the wind

Vector wind computations

     $\overline{U}_{RV}$ resultant mean wind speed

     $\overline{\theta}_{RV}$ resultant mean wind direction

     $\overline{\theta}_{UV}$ unit vector mean wind direction

     V_e magnitude of the east-west component of the resultant vector mean wind (positive towards east)

     V_n magnitude of the north-south component of the resultant vector mean wind (positive towards the north)

     V_x magnitude of the east-west component of the unit vector mean wind

     V_y magnitude of the north-south component of the unit vector mean wind

     x,y,z standard right-hand-rule coordinate system with x-axis aligned towards the east.

6.2.1 Scalar Computations

The scalar mean wind speed is:

$$\bar{u} = \frac{1}{N} \sum_1^N u_i \qquad \text{(6.2.1)}$$

The harmonic mean wind speed is:

$$\bar{u}_h = \left(\frac{1}{N} \sum_1^N \frac{1}{u_i} \right)^{-1} \qquad \text{(6.2.2)}$$

The standard deviation of the horizontal component of the wind speed is:

$$\sigma_u = \left[\frac{1}{N} \left\{ \sum_1^N u_i^2 - \frac{1}{N} \left(\sum_1^N u_i \right)^2 \right\} \right]^{\frac{1}{2}} \qquad \text{(6.2.3)}$$

The wind direction is a circular function with values between 1 and 360 degrees. The wind direction discontinuity at the beginning/end of the scale requires special processing to compute a valid mean value. A single-pass procedure developed by Mitsuta and documented in reference [23] is recommended. The method assumes that the difference between successive wind direction samples is less than 180 degrees; to ensure such, a sampling rate of once per second or greater should be used (see Section 6.2.4). Using the Mitsuta method, the scalar mean wind direction is computed as:

$$\bar{\theta} = \frac{1}{N} \sum_1^N D_i \qquad \text{(6.2.4)}$$

where $D_i = \theta_i$; for $I = 1$

$D_i = D_{i-1} + \delta_i + 360$; for $\delta_i < -180$ and $I > 1$

$D_i = D_{i-1} + \delta_i$; for $|\delta_i| < 180$ and $I > 1$

$D_i = D_{i-1} + \delta_i - 360$; for $\delta_i > 180$ and $I > 1$

D_i is undefined for $\delta_i = 180$ and $I > 1$

$\delta_i = \theta_i - D_{i-1}$; for $I > 1$

θ_i is the azimuth angle of the wind vane for the ith sample.

The following notes/cautions apply to the determination of the scalar mean wind direction using Equation. 6.2.4:

- If the result is less than zero or greater than 360, increments of 360 degrees should be added or subtracted, as appropriate, until the result is between zero and 360 degrees.

- Erroneous results may be obtained if this procedure is used to post-process sub-hourly averages to obtain an hourly average. This is because there can be no guarantee that the difference between successive sub-hourly averages will be less than 180 degrees.

The scalar mean wind direction, as defined in Equation. 6.2.4, retains the essential statistical property of a mean value, namely that the deviations from the mean must sum to zero:

$$\sum (\theta_i - \bar{\theta}) = 0 \qquad (6.2.5)$$

By definition, the same mean value must be used in the calculation of the variance of the wind direction and, likewise, the standard deviation (the square root of the variance). The variance of the wind direction is given by:

$$\sigma_\theta^2 = \frac{1}{N} \sum (\theta_i - \bar{\theta})^2 \qquad (6.2.6)$$

The standard deviation of the wind direction using the Mitsuta method is given by:

$$\sigma_A = \sigma_\theta = \left[\frac{1}{N} \left\{ \sum_1^N D_i^2 - \frac{1}{N} \left(\sum_1^N D_i \right)^2 \right\} \right]^{1/2} \qquad (6.2.7)$$

Cases may arise in which the sampling rate is insufficient to assure that differences between successive wind direction samples are less than 180 degrees. In such cases, approximation formulas may be used for computing the standard deviation of the wind direction. Mardia [24] shows that a suitable estimate of the standard deviation (in radian measure) is:

$$\sigma_A = \sigma_\theta = \left[-2 \ln(R) \right]^{1/2} \qquad (6.2.8)$$

where
$$R = (Sa^2 + Ca^2)^{1/2}$$
$$Sa = \frac{1}{N} \sum_1^N \sin(\theta_i)$$
$$Ca = \frac{1}{N} \sum_1^N \cos(\theta_i)$$

Several methods for calculating the standard deviation of the wind direction were evaluated by Turner **[25]**; a method developed by Yamartino **[26]** was found to provide excellent results for most cases. The Yamartino method is given in the following:

$$\sigma_A = \sigma_\theta = \mathbf{arcsin(\epsilon)} \ [\mathbf{1. + 0.1547 \ \epsilon^3}] \tag{6.2.9}$$

where
$$\epsilon = \left[\mathbf{1.} - \left(\overline{\mathbf{sin(\theta_i)}}^{\ 2} + \overline{\mathbf{cos(\theta_i)}}^{\ 2} \right) \right]^{1/2}$$

Note that hourly σ_θ values computed using 6.2.7, 6.2.8, or 6.2.9 may be inflated by contributions from long period oscillations associated with light wind speed conditions (e.g., wind meander). To minimize the effects of wind meander, the hourly σ_θ (for use e.g., in stability determinations - see Section 6.4.4.4) should be calculated based on four 15-minute values averaged as follows:

$$\sigma_\theta(1{-}hr) = \left[\left\{ (\sigma_{\theta_1})^2 + (\sigma_{\theta_2})^2 + (\sigma_{\theta_3})^2 + (\sigma_{\theta_4})^2 \right\} /4 \right]^{1/2} \tag{6.2.10}$$

The standard deviation of the vertical component of the wind speed is:

$$\sigma_w = \left[\frac{1}{N} \left\{ \sum_1^N w_i^2 - \frac{1}{N} \left(\sum_1^N w_i \right)^2 \right\} \right]^{1/2} \tag{6.2.11}$$

Similarly, the standard deviation of the elevation angle of the wind vector is:

$$\sigma_E = \sigma_\phi = \left[\frac{1}{N} \left\{ \sum_1^N \phi_i^2 - \frac{1}{N} \left(\sum_1^N \phi_i \right)^2 \right\} \right]^{1/2} \tag{6.2.12}$$

Equation 6.2.12 is provided for completeness only. The bivane, which is used to measure the elevation angle of the wind, is regarded as a research grade instrument and is not recommended for routine monitoring applications. See Section 6.2.3 for recommendations on estimating σ_ϕ.

6.2.2   Vector Computations

From the sequence of N observations of θ_i and u_i, the mean east-west, V_e, and north-south, V_n, components of the wind are:

$$V_e = -\frac{1}{N} \sum u_i \ sin(\theta_i) \tag{6.2.13}$$

$$V_n = -\frac{1}{N} \sum u_i \cos(\theta_i) \qquad\qquad (6.2.14)$$

The resultant mean wind speed and direction are:

$$\overline{U}_{RV} = (V_e^2 + V_n^2)^{1/2} \qquad\qquad (6.2.15)$$

$$\overline{\theta}_{RV} = ArcTan\ (V_e/V_n) + FLOW \qquad\qquad (6.2.16)$$

where
$$FLOW \begin{array}{l} = +180; \quad for\ ArcTan(V_e/V_n) < 180 \\ = -180; \quad for\ ArcTan(V_e/V_n) > 180 \end{array}$$

Equation 6.2.16 assumes the angle returned by the ArcTan function is in degrees. This is not always the case and depends on the computer processor. Also, the ArcTan function can be performed several ways. For instance, in FORTRAN either of the following forms could be used:

$$ATAN(V_e/V_n)$$

or $\quad ATAN2(V_e,\ V_n).$

The ATAN2 form avoids the extra checks needed to insure that V_n is nonzero, and is defined over a full 360 degree range.

The unit vector approach to computing mean wind direction is similar to the vector mean described above except that the east-west and north-south components are not weighted by the wind speed. Using the unit vector approach, equations 6.2.13 and 6.2.14 become:

$$V_x = -\frac{1}{N} \sum Sin\ \theta_i \qquad\qquad (6.2.17)$$

$$V_y = -\frac{1}{N} \sum Cos\theta_i \qquad\qquad (6.2.18)$$

The unit vector mean wind direction is:

$$\overline{\theta}_{UV} = ArcTan\ (V_x/V_y) + FLOW \tag{6.2.19}$$

where
$$FLOW \begin{array}{ll} = & +180; \quad for\ ArcTan(V_x/V_y) < 180 \\ = & -180; \quad for\ ArcTan(V_x/V_y) > 180 \end{array}$$

In general, the unit vector result will be comparable to the scalar average wind direction, and may be used to model plume transport.

6.2.3   Treatment of Calms

Calms, periods with little or no air movement, require special consideration in air quality evaluations; one of the more important considerations involves model selection. If the limiting air quality conditions are associated with calms, then a non-steady-state model, such as CALPUFF **[27]**, should be used. The use of a time varying 3-dimensional flow field in this model enables one to simulate conditions which are not applicable to steady-state models; e.g., recirculations and variable trajectories. Guidance for preparing meteorological data for use in CALPUFF is provided in the user's guide to the meteorological processor for this model **[28]**.

Steady-state models may be used for regulatory modeling applications if calms are not expected to be limiting for air quality. Calms require special treatment in such applications to avoid division by zero in the steady-state dispersion algorithm. EPA recommended steady-state models such as ISCST accomplish this with routines that nullify concentrations estimates for calm conditions and adjust short-term and annual average concentrations as appropriate. The EPA CALMPRO **[29]** program post-processes model output to achieve the same effect for certain models lacking this built-in feature. For similar reasons, to avoid unrealistically high concentration estimates at low wind speeds (below the values used in validations of these models - about 1 m/s) EPA recommends that wind speeds less than 1 m/s be reset to 1 m/s for use in steady-state dispersion models; the unaltered data should be retained for use in non-steady-state modeling applications. Calms should be identified in processed data files by flagging the appropriate records; user's guides for the model being used should be consulted for model specific flagging conventions.

For the purposes of this guidance and for the objective determination of calm conditions applicable to in situ monitoring, a calm occurs when the wind speed is below the starting threshold of the anemometer or vane, whichever is greater. For site-specific monitoring (using the recommended thresholds for wind direction and wind speed given in Table 5-2) a calm occurs when the wind speed is below 0.5 m/s. One should be aware that the frequency of calms are typically higher for NWS data bases because the sensors used to measure wind speed and wind direction have a higher threshold - typically 2 kts (1 m/s) - see Section 6.7.

6-7

6.2.4   Turbulence

6.2.4.1 Estimating σ_E from σ_w

Applications requiring the standard deviation of the elevation angle of the wind (e.g., see Section 6.4.4) should use the following approximation:

$$\sigma_E = \sigma_w/\bar{u} \qquad\qquad (6.2.20)$$

where σ_E is the standard deviation of the elevation angle of the wind (radians)

   σ_w is the standard deviation of the vertical component of the wind speed (m/s)

   $\bar{u}$ is the scalar mean wind speed (m/s).

Weber et. al. [30] reported good performance for an evaluation using data measured at the Savannah River Laboratory for wind speeds greater than 2 m/s. In a similar study, Deihl [31] reported satisfactory performance for wind speeds greater than 2 m/s. In the Deihl study, the performance varied depending on the overall turbulence intensity. It is concluded from these studies that σ_E is best approximated by $\sigma_w/\bar{u}$ when wind speeds are greater than 2 m/s, and σ_E is greater than 3 degrees.

6.2.5   Wind Speed Profiles

Dispersion models recommended for regulatory applications employ algorithms for extrapolating the input wind speed to the stack-top height of the source being modeled; the wind speed at stack-top is used for calculating transport and dilution. This section provides guidance for implementing these extrapolations using default parameters and recommends procedures for developing site specific parameters for use in place of the defaults.

For convenience, in non-complex terrain up to a height of about 200 m above ground level, it is assumed that the wind profile is reasonably well approximated as a power-law of the form:

$$U_z = U_r(Z/Z_r)^p \qquad\qquad (6.2.21)$$

where $U_z =$ the scalar mean wind speed at height z above ground level

   $U_r =$ the scalar mean wind speed at some reference height Z_r, typically 10 m

   $p =$ the power-law exponent.

The power-law exponent for wind speed typically varies from about 0.1 on a sunny afternoon to about 0.6 during a cloudless night. The larger the power-law exponent the larger the vertical gradient in the wind speed. Although the power-law is a useful engineering approximation of the average wind speed profile, actual profiles will deviate from this relationship.

Site-specific values of the power-law exponent may be determined for sites with two levels of wind data by solving Equation (6.2.20) for p:

$$p = \frac{\ln(U) - \ln(U_r)}{\ln(Z) - \ln(Z_r)} \tag{6.2.21}$$

As discussed by Irwin [32], wind profile power-law exponents are a function of stability, surface roughness and the height range over which they are determined. Hence, power-law exponents determined using two or more levels of wind measurements should be stratified by stability and surface roughness. Surface roughness may vary as a function of wind azimuth and season of the year (see Section 6.4.2). If such variations occur, this would require azimuth and season dependent determination of the wind profile power-law exponents. The power-law exponents are most applicable within the height range and season of the year used in their determination. Use of these wind profile power-law exponents for estimating the wind at levels above this height range or to other seasons should only be done with caution. The default values used in regulatory models are given in Table 6-2.

Table 6-2

Recommended Power-law Exponents for Urban and Rural Wind Profiles

Stability Class	Urban Exponent	Rural Exponent
A	0.15	0.07
B	0.15	0.07
C	0.20	0.10
D	0.25	0.15
E	0.30	0.35
F	0.30	0.55

The following discussion presents a method for determining at what levels to specify the wind speed on a multi-level tower to best represent the wind speed profile in the vertical. The problem can be stated as, what is the percentage error resulting from using a linear interpolation over a height interval (between measurement levels), given a specified value for the power-law

exponent. Although the focus is on wind speed, the results are equally applicable to profiles of other meteorological variables that can be approximated by power laws.

Let U_l represent the wind speed found by linear interpolation and U the "correct" wind speed. Then the fractional error is:

$$FE \;=\; (U_l - U)/U \tag{6.2.22}$$

The fractional error will vary from zero at both the upper, Z_u, and lower, Z_l, bounds of the height interval, to a maximum at some intervening height, Z_m. If the wind profile follows a power law, the maximum fractional error and the height at which it occurs are:

$$FE_{max} \;=\; \frac{(Z_l/Z_r)^p \;-\; (Z_m/Z_r)^p \;+\; A(Z_m - Z_l)/(Z_u - Z_l)}{(Z_m/Z_r)^p} \tag{6.2.23}$$

where

$$A \;=\; (Z_u/Z_r)^p \;-\; (Z_l/Z_r)^p$$

and

$$Z_m \;=\; [pZ_l/(p-1)] \;-\; [p/(p-1)]\,(Z_l/Z_r)^p\,(Z_u - Z_l)/A$$

As an example, assume p equals 0.34 and the reference height, Z_r, is 10 m. Then for the following height intervals, the maximum percentage error and the height at which it occurs are:

Interval (m)	Maximum Error (%)	Height of Max Error (m)
2 - 10	-6.83	4.6
10 - 25	-2.31	16.0
25 - 50	-1.33	35.6
50 - 100	-1.33	71.2

As expected, the larger errors occur for the lower heights where the wind speed changes most rapidly with height. Thus, sensors should be spaced more closely together in the lower heights to best approximate the actual profile. Since the power-law is only an approximation of the actual profile, errors can occur that are larger than those estimated using (6.2.22). Even with this limitation, the methodology is useful for determining the optimum heights to place a limited number of wind sensors. The height Z_m represents the optimum height to place a third sensor given the location of the two surrounding sensors.

6.3   Temperature

Temperature is used in calculations to determine plume rise (Section 6.3.1), mixing height (Section 6.5), and various surface-layer parameters (Section 6.6). Unless indicated otherwise, ambient temperature measurements should be used in these calculations. Although not essential, the ambient temperature may also be used for consistency checking in QA procedures. Applications of vertical temperature gradient measurements are discussed in Section 6.3.2.

6.3.1   Use in Plume-Rise Estimates

Temperature is used in calculating the initial buoyancy flux in plume rise calculations as follows:

$$F \;\; = \;\; g(T_p - T_e)V/T_p \tag{6.3.1}$$

where the subscripts p and e indicate the plume and environmental values, respectively, and V is the volume flux [13].

6.3.2   Vertical Temperature Gradient

Vertical temperature gradient measurements are used for classifying stability in the surface layer, in various algorithms for calculating surface scaling parameters, and in plume rise equations for stable conditions. For all of these applications the relative accuracy and resolution of the thermometers are of critical importance. Recommended heights for temperature gradient measurements in the surface layer are 2 m and 10 m. For use in estimating plume rise in stable conditions, the vertical temperature gradient should be determined using measurements across the plume rise layer; a minimum height separation of 50 m is recommended for this application.

6.4   Stability

Stability typing is employed in air quality dispersion modeling to facilitate estimates of lateral and vertical dispersion parameters [e.g., the standard deviation of plume concentration in the lateral (σ_y) and vertical (σ_z)] used in Gaussian plume models. The preferred stability typing scheme, recommended for use in regulatory air quality modeling applications is the scheme proposed in an article by Pasquill in 1961 [33]; the dispersion parameters associated with this scheme [often referred to as the Pasquill-Gifford (P-G) sigma curves] are used by default in most of the EPA recommended Gaussian dispersion models.

Table 6-3 provides a key to the Pasquill stability categories as originally defined; though impractical for routine application, the original scheme provided a basis for much of the

developmental work in dispersion modeling. For routine applications using the P-G sigmas, the Pasquill stability category (hereafter referred to as the P-G stability category) should be calculated using the method developed by Turner [34]; Turner's method is described in Section 6.4.1. Subsequent sections describe alternative methods for estimating the P-G stability category when representative cloud cover and ceiling data are not available. These include a radiation-based method which uses measurements of solar radiation during the day and delta-T at night (Section 6.4.2) and turbulence-based methods which use wind fluctuation statistics (Sections 6.4.3 and 6.4.4). Procedures for the latter are based on the technical note published by Irwin in 1980 [35]; user's are referred to the technical note for background on the estimation of P-G stability categories.

Table 6-3

Key to the Pasquill Stability Categories

Surface wind speed (m/s)	Daytime Insolation			Nighttime cloud cover	
	Strong	Moderate	Slight	Thinly overcast or ≥4/8 low cloud	≤ 3/8
< 2	A	A - B	B	-	-
2 - 3	A - B	B	C	E	F
3 - 5	B	B - C	C	D	E
5 - 6	C	C - D	D	D	D
> 6	C	D	D	D	D

Strong insolation corresponds to sunny, midday, midsummer conditions in England; slight insolation corresponds to similar conditions in midwinter. Night refers to the period from one hour before sunset to one hour after sunrise. The neutral category, D, should be used regardless of wind speed, for overcast conditions during day or night.

6.4.1   Turner's method

Turner [34] presented a method for determining P-G stability categories from data that are routinely collected at National Weather Service (NWS) stations. The method estimates the effects of net radiation on stability from solar altitude (a function of time of day and time of year), total cloud cover, and ceiling height. Table 6-4 gives the stability class (1=A, 2=B,...) as a function of wind speed and net radiation index. Since the method was developed for use with NWS data, the wind speed is given in knots. The net radiation index is related to the solar altitude (Table 6-5) and is determined from the procedure described in Table 6-6. Solar altitude can be determined from the Smithsonian Meteorological Tables [36]. For EPA regulatory

modeling applications, stability categories 6 and 7 (F and G) are combined and considered category 6.

Table 6-4

Turner's Key to the P-G Stability Categories

Wind Speed		Net Radiation Index						
(knots)	(m/s)	4	3	2	1	0	-1	-2
0,1	0 - 0.7	1	1	2	3	4	6	7
2,3	0.8 - 1.8	1	2	2	3	4	6	7
4,5	1.9 - 2.8	1	2	3	4	4	5	6
6	2.9 - 3.3	2	2	3	4	4	5	6
7	3.4 - 3.8	2	2	3	4	4	4	5
8,9	3.9 - 4.8	2	3	3	4	4	4	5
10	4.9 - 5.4	3	3	4	4	4	4	5
11	5.5 - 5.9	3	3	4	4	4	4	4
≥ 12	≥ 6.0	3	4	4	4	4	4	4

Table 6-5

Insolation Class as a Function of Solar Altitude

Solar Altitude Φ (degrees)	Insolation	Insolation Class Number
$60 < \Phi$	strong	4
$35 < \Phi \leq 60$	moderate	3
$15 < \Phi \leq 35$	slight	2
$\Phi \leq 15$	weak	1

Table 6-6

Procedure for Determining the Net Radiation Index

1.   If the total cloud[1] cover is 10/10 and the ceiling is less than 7000 feet, use net radiation index equal to 0 (whether day or night).

2. For nighttime: (from one hour before sunset to one hour after sunrise):
       (a)   If total cloud cover $\leq$ 4/10, use net radiation index equal to -2.

       (b)   If total cloud cover > 4/10, use net radiation index equal to -1.

3. For daytime:

       (a)   Determine the insolation class number as a function of solar altitude from Table 6-5.

       (b)   If total cloud cover $\leq$ 5/10, use the net radiation index in Table 6-4 corresponding to the isolation class number.

       ©   If cloud cover >5/10, modify the insolation class number using the following six steps.

           (l)   Ceiling <7000 ft, subtract 2.

           (2)   Ceiling $\geq$ 7000 ft but <16000 ft, subtract 1.

           (3)   total cloud cover equal 10/10, subtract 1. (This will only apply to ceilings $\geq$ 7000 ft since cases with 10/10 coverage below 7000 ft are considered in item 1 above.)

           (4)   If insolation class number has not been modified by steps (1), (2), or (3) above, assume modified class number equal to insolation class number.

           (5)   If modified insolation class number is less than 1, let it equal 1.

           (6)   Use the net radiation index in Table 6-4 corresponding to the modified insolation class number.

---

[1]   *Although Turner indicates total cloud cover, opaque cloud cover is implied by Pasquill and is preferred; EPA recommended meteorological processors, MPRM and PCRAMMET, will accept either.*

6.4.2 Solar radiation/delta-T (SRDT) method

The solar radiation/delta-T (SRDT) method retains the basic structure and rationale of Turner's method while obviating the need for observations of cloud cover and ceiling. The method, outlined in Table 6-7, uses the surface layer wind speed (measured at or near 10 m) in combination with measurements of total solar radiation during the day and a low-level vertical temperature difference (ΔT) at night (see Section 3.1.2.1 for guidance on probe placement for measurement of the surface layer ΔT). The method is based on Bowen et al. **[37]** with modifications as necessary to retain as much as possible of the structure of Turner's method.

Table 6-7

Key to Solar Radiation Delta-T (SRDT) Method for Estimating

Pasquill-Gifford (P-G) Stability Categories

DAYTIME

Wind Speed (m/s)	Solar Radiation (W/m^2)			
	≥ 925	925 - 675	675 - 175	< 175
< 2	A	A	B	D
2 - 3	A	B	C	D
3 - 5	B	B	C	D
5 - 6	C	C	D	D
≥ 6	C	D	D	D

NIGHTTIME

Wind Speed (m/s)	Vertical Temperature Gradient	
	< 0	≥ 0
< 2.0	E	F
2.0 - 2.5	D	E
≥ 2.5	D	D

6.4.3 σ_E method

The σ_E method (Tables 6-8a and 6-8b) is a turbulence-based method which uses the standard deviation of the elevation angle of the wind in combination with the scalar mean wind speed.

The criteria in Table 6-8a and Table 6-8b are for data collected at 10m and a roughness length of 15 cm. Wind speed and direction data collected within the height range from $20z_0$ to $100z_0$ should be used. For sites with very low roughness, these criteria are slightly modified. The lower bound of measurement height should never be less than 1.0 m; the upper bound should never be less than 10 m. To obtain 1-hour averages, the recommended sampling duration is 15 minutes, but it should be at least 3 minutes and may be as long as 60 minutes. The relationships employed in the estimation methods assume conditions are steady state. This is more easily achieved if the sampling duration is less than 30 minutes.

Table 6-8a

Vertical Turbulence[a] Criteria for Initial Estimate of Pasquill-Gifford (P-G)

Stability Category. For use with Table 6-7b.

Initial estimate of P-G stability category	Standard deviation of wind elevation angle σ_E (degrees)
A	$11.5 \leq \sigma_E$
B	$10.0 \leq \sigma_E < 11.5$
C	$7.8 \leq \sigma_E < 10.0$
D	$5.0 \leq \sigma_E < 7.8$
E	$2.4 \leq \sigma_E < 5.0$
F	$\sigma_E < 2.4$

[a] As indicated by the standard deviation of the elevation angle of the wind vector, σ_ϕ. Sigma-E and σ_E are aliases for σ_ϕ.

Table 6-8b

Wind Speed Adjustments for Determining Final Estimate of P-G Stability

Category from σ_E. For use with Table 6-8a.

Initial estimate of P-G Category		10-meter wind speed (m/s)	Final estimate of P-G Category
Daytime	A	$u < 3$	A
	A	$3 \le u < 4$	B
	A	$4 \le u < 6$	C
	A	$6 \le u$	D
	B	$u < 4$	B
	B	$4 \le u < 6$	C
	B	$6 \le u$	D
	C	$u < 6$	C
	C	$6 \le u$	D
	D, E, or F	ANY	D
Nighttime	A	ANY	D
	B	ANY	D
	C	ANY	D
	D	ANY	D
	E	$u < 5$	E
	E	$5 \le u$	D
	F	$u < 3$	F
	F	$3 \le u < 5$	E
	F	$5 \le u$	D

If the site roughness length is other than 15 cm, the category boundaries listed in Table 6-8a may need to be adjusted. As an initial adjustment, multiply the Table 6-8a values by:

$$(z_o/15)^{0.2}$$

where z_o is the site roughness in centimeters. This factor, while theoretically sound, has not had widespread testing. It is likely to be a useful adjustment for cases when z_o is greater than 15 cm. It is yet problematical whether the adjustment is as useful for cases when z_o is less than 15 cm.

If the measurement height is other than 10 m, the category boundaries listed in Table 6-8a will need to be adjusted. As an initial adjustment, multiply the lower bound values by:

$$(Z/10)^{P_\phi}$$

where Z is the measurement height in meters. The exponent P_ϕ is a function of the P-G stability category with values as follows:

P-G Stability	P_ϕ
A	0.02
B	0.04
C	0.01
D	-0.14
E	-0.31

The above suggestions summarize the results of several studies conducted in fairly ideal circumstances. It is anticipated that readers of this document are often faced with conducting analyses in less than ideal circumstances. Therefore, before trusting the Pasquill category estimates, the results should be spot checked. This can easily be accomplished. Choose cloudless days. In mid-afternoon during a sunny day, categories A and B should occur. During the few hours just before sunrise, categories E and F should occur. The bias, if any, in the turbulence criteria will quickly be revealed through such comparisons. Minor adjustments to the category boundaries will likely be needed to tailor the turbulence criteria to the particular site characteristics, and should be made in consultation with the reviewing agency.

6.4.4 σ_A method

The σ_A method (Tables 6-9a and 6-9b) is a turbulence-based method which uses the standard deviation of the wind direction in combination with the scalar mean wind speed. The criteria in Table 6-9a and Table 6-9b are for data collected at 10 m and a roughness length of 15 cm. Wind speed and direction data collected within the height range from $20z_o$ to $100z_o$ should be used. For sites with very low roughness, these criteria are slightly modified. The lower bound

measurement height should never be less than 1 m. The upper bound should never be less than 10 m. To obtain 1-hour averages, the recommended sampling duration is 15 minutes, but it should be at least 3 minutes and may be as long as 60 minutes. The relationships employed in the estimation methods assume conditions are steady state. This is more easily achieved if the sampling duration is less than 30 minutes. To minimize the effects of wind meander, the 1-hour σ_A is defined using 15-minute values (see Equation. 6.2.10).

Table 6-9a

Lateral Turbulence[a] Criteria for Initial Estimate of Pasquill-Gifford (P-G)

Stability Category. For use with Table 6-8b.

Initial estimate of P-G stability category	Standard deviation of wind azimuth angle σ_A
A	$22.5 \leq \sigma_A$
B	$17.5 \leq \sigma_A < 22.5$
C	$12.5 \leq \sigma_A < 17.5$
D	$7.5 \leq \sigma_A < 12.5$
E	$3.8 \leq \sigma_A < 7.5$
F	$\sigma_A < 3.8$

[a] As indicated by the standard deviation of the azimuth angle of the wind vector, σ_θ. Sigma-A, Sigma-Theta, and σ_A are aliases for σ_θ.

Table 6-9b

Wind Speed Adjustments for Determining Final Estimate of P-G Stability

Category from σ_A. For use with Table 6-9a.

Initial estimate of P-G Category		10-meter wind speed (m/s)	Final estimate of P-G Category
Daytime	A	$u < 3$	A
	A	$3 \leq u < 4$	B
	A	$4 \leq u < 6$	C
	A	$6 \leq u$	D
	B	$u < 4$	B
	B	$4 \leq u < 6$	C
	B	$6 \leq u$	D
	C	$u < 6$	C
	C	$6 \leq u$	D
	D, E, or F	ANY	D
Nighttime	A	$u < 2.9$	F
	A	$2.9 \leq u < 3.6$	E
	A	$3.6 \leq u$	D
	B	$u < 2.4$	F
	B	$2.4 \leq u < 3.0$	E
	B	$3.0 \leq u$	D
	C	$u < 2.4$	E
	C	$2.4 \leq u$	D
	D	ANY	D
	E	$u < 5$	E
	E	$5 \leq u$	D
	E		
	F	$u < 3$	F
	F	$3 \leq u < 5$	E
	F	$5 \leq u$	D

.

If the site roughness length is other than 15 cm, the category boundaries listed in Table 6-9a may need adjustment. As an initial adjustment, multiply the values listed by:

$$(z_o/15)^{0.2}$$

where z_o is the site roughness in centimeters. This factor, while theoretically sound, has not had widespread testing. It is likely to be a useful adjustment for cases when z_o is greater than 15 cm. It is yet problematical whether the adjustment is as useful for cases when z_o is less than 15 cm.

If the measurement height is other than 10 m, the category boundaries listed in Table 6-9a will need adjustment. As an initial adjustment, multiply the lower bound values listed by:

$$(Z/10)^{P_\theta}$$

where Z is the measurement height in meters.

The exponent P_θ is a function of the P-G stability category with values as follows:

P-G Stability	P_θ
A	-0.06
B	-0.15
C	-0.17
D	-0.23
E	-0.38

The above suggestions summarize the results of several studies conducted in fairly ideal circumstances. It is anticipated that readers of this document are often faced with conducting analyses in less than ideal circumstances. Therefore, before trusting the Pasquill category estimates, the results should be spot checked. This can easily be accomplished. Choose cloudless days. In mid-afternoon during a sunny day, categories A and B should occur. During the few hours just before sunrise, categories E and F should occur. The bias, if any, in the turbulence criteria will quickly be revealed through such comparisons. Minor adjustments to the category boundaries will likely be needed to tailor the turbulence criteria to the particular site characteristics, and should be made in consultation with the reviewing agency.

6.4.5 Accuracy of stability category estimates

By virtue of its historic precedence and widespread use, EPA considers Turner's method [34] to be the benchmark procedure for determining P-G stability. Evaluations performed in developing the SRDT method indicate that this method identifies the same P-G stability category

as Turner's method (Section 6.4.1) about 60 percent of the time and is within one category about 90 percent of the time (EPA, 1994) **[38]**. Results are not available comparing the performance of the σ_A and σ_E methods outlined above in this section. However, there are comparison results for similar methods. From these studies, it is concluded that the methods will estimate the same stability category about 50 percent of the time and will be within one category about 90 percent of the time. Readers are cautioned that adjustment of the turbulence criteria resulting from spot checks is necessary to achieve this performance. For additional information on stability classification using wind fluctuation statistics, see references **[39]**, **[40]**, **[41]**, and **[42]**.

6.5   Mixing Height

For the purposes of this guidance, mixing height is defined as the height of the layer adjacent to the ground over which an emitted or entrained inert non-buoyant tracer will be mixed (by turbulence) within a time scale of about one hour or less **[43]**.   Taken literally, the definition means that routine monitoring of the mixing height is generally impractical. For routine application, alternative methods are recommended for estimating mixing heights based on readily available data.

The Holzworth method **[44]** is recommended for use when representative NWS upper-air data are available. This procedure relies on the general theoretical principle that the lapse rate is roughly dry adiabatic (no change in potential temperature with height) in a well-mixed daytime convective boundary layer (CBL); the Holzworth method is described in Section 6.5.1. Other alternatives include using estimates of mixing heights provided in CBL model output (Weil and Brower **[45]**; Paine **[46]**) and mixing heights derived from remote sensing measurements of turbulence or turbulence related parameters; the latter are discussed in Section 9.1.1.

6.5.1   The Holzworth Method

The Holzworth method **[44]** provides twice-per-day (morning and afternoon) mixing heights based on calculations using routine NWS upper-air data. The morning mixing height is calculated as the height above ground at which the dry adiabatic extension of the morning minimum surface temperature plus 5°C intersects the vertical temperature profile observed at 1200 Greenwich Mean Time (GMT). The minimum temperature is determined from the regular hourly airways reports from 0200 through 0600 Local Standard Time (LST). The "plus 5°C " was intended to allow for the effects of the nocturnal and early morning urban heat island since NWS upper-air stations are generally located in rural or suburban surroundings.   However, it can also be interpreted as a way to include the effects of some surface heating shortly after sunrise. Thus, the time of the urban morning mixing height coincides approximately with that of the typical diurnal maximum concentration of slow-reacting pollutants in many cities, occurring around the morning commuter rush hours.

The afternoon mixing height is calculated in the same way, except that the maximum surface temperature observed from 1200 through 1600 LST is used. Urban-rural differences of maximum surface temperature are assumed negligible. The typical time of the afternoon mixing height may be considered to coincide approximately with the usual mid-afternoon minimum concentration of slow-reacting urban pollutants.

Hourly mixing heights, for use in regulatory dispersion modeling, are interpolated from these twice per day estimates. The recommended interpolation procedure is provided in the user's guide for the Industrial Source Complex (ISC) dispersion model **[47]**.

6.6   Boundary Layer Parameters

This section provides recommendations for monitoring in support of air quality dispersion models which incorporate boundary layer scaling techniques.   The applicability of these techniques is particularly sensitive to the measurement heights for temperature and wind speed;   the recommendations for monitoring, given in Section 6.6.4, consequently, focus on the placement of the temperature and wind speed sensors. A brief outline of boundary layer theory, given in the following, provides necessary context for these recommendations.   The references for this section **[48]**, **[49]**, **[50]**, **[51]**, **[52]**, **[53]**, **[54]**, **[55]**, **[56]**, **[57]**, **[58]**, **[59]** provide more detailed information on boundary layer theory.

The Atmospheric Boundary Layer (ABL) can be defined as the lower layer of the atmosphere, where processes which contribute to the production or destruction of turbulence are significant; it is comprised of two layers, a lower surface layer, and a so-called "mixed" upper layer.   The height of the ABL during daytime roughly coincides with the height to which pollutants are mixed (the mixing height, Section 6.5). During night-time stable conditions, the mixing height (h) is an order of magnitude smaller than the maximum daytime value over land; at night, h is typically below the top of the surface-based radiation inversion **[57]**.

The turbulent structure of the ABL is determined by the amount of heat released to the atmosphere from the earth's surface (sensible heat flux) and by interaction of the wind with the surface (momentum flux). This structure can be described using three length scales: z (the height above the surface), h (the mixing height), and L (the Obukhov length). The Obukhov length is defined by the surface fluxes of heat $H = \rho C_p \ \overline{w'\theta'}$ and momentum $u_*^2 \ = \ -\overline{u'w'}$, and reflects the height at which contributions to the turbulent kinetic energy from buoyancy and shear stress are comparable; the Obukhov length is defined as:

$$ L \ = \ \frac{- \, u_*^3}{k \ (g/\theta) \ \overline{w'\theta'}} \tag{6.6.1} $$

where k is the von Karman constant, θ is the mean potential temperature within the surface layer, g/θ is a buoyancy parameter, and u_* is the friction velocity. The three length scales define two independent non-dimensional parameters: a relative height scale (z/h), and a stability index (h/L)**[56]**.

Alternatives to the measurement of the surface fluxes of heat and momentum for use in (6.6.1) involve relating turbulence to the mean profiles of temperature and wind speed. The Richardson number, the ratio of thermal to mechanical production (destruction) of turbulent kinetic energy, is directly related to another non-dimensional stability parameter (z/L) and, thus, is a good candidate for an alternative to 6.6.1. The gradient Richardson number (R_g) can be approximated by:

$$ R_g \ = \ \frac{g}{T} \ \frac{\Delta\theta}{(\Delta u)^2} \ (z_2 - z_1) \tag{6.6.2} $$

6-24

Large negative Richardson numbers indicate unstable conditions while large positive values indicate stable conditions. Values close to zero are indicative of neutral conditions. Use of (6.6.2) requires estimates of Δu based on measurements of wind speed at two levels in the surface layer; however, the level of accuracy required for these measurements is problematic (Δu is typically the same order of magnitude as the uncertainty in the wind speed measurement). The bulk Richardson number (R_b) which can be computed with only one level of wind speed is a more practical alternative:

$$R_b = \frac{g}{\overline{T}} \frac{\Delta\theta}{u^2} z$$

(6.6.3)

6.6.1   The Profile Method

The bulk Richardson number given in (6.6.3) is perhaps the simplest and most direct approach for characterizing the surface layer. For example, given the necessary surface layer measurements, one can derive both H and u_* from the integrated flux-profile equations: **[51,52]**

$$\Delta u = \frac{u_*}{k}\left[\ln\left(\frac{z_{i+1}}{z_i}\right) - \psi_m\left(\frac{z_{i+1}}{L}\right) + \psi_m\left(\frac{z_i}{L}\right)\right]$$

(6.6.4)

$$\Delta\theta = R\frac{\theta_*}{k}\left[\ln\left(\frac{z_{j+1}}{z_j}\right) - \psi_h\left(\frac{z_{j+1}}{L}\right) + \psi_h\left(\frac{z_j}{L}\right)\right]$$

(6.6.5)

where $\Delta u = (u_{i+1} - u_i)$, $\Delta\theta = (\theta_{j+1} - \theta_j)$; R is a parameter associated with the emperically determined similarity functions, ψ_m and ψ_h. EPA recommends using the emperical functions given in reference **[59]**; in this case the von Karman constant, k = 0.4 and R = 1. The temperature scale θ_* is related to the heat flux by:

$$H = -\rho\, C_p\, u_*\, \theta_*$$

(6.6.6)

Methods for solving the flux profile equations vary depending on what measurements are available. In the general case with two arbitrary levels each of temperature and wind speed [i.e., as in (6.6.4) and (6.6.5)], one can solve for the unknowns (u_*, θ_*, and L) by iteration; when temperature and wind speed are measured at the same heights, approximate analytic solutions can

be used.   Other simplifications result by replacing the lower wind speed measurement height in (6.6.4), z_i, with the surface roughness length (z_0) [51,52] ; see Section 6.6.3 for guidance on estimating surface roughness. A least squares method [49] is recommended when wind speed and temperature data are available for three or more levels. To ensure the data are representative of the surface layer, the wind speed and tempreature sensors should be located between $20z_0$ and $100z_0$; for sites with very low roughness, the sensors should be located between 1 and 10 m. Sampling durations for use in computing 1-hour averages should be in the range of 3 to 60 minutes; a sampling duration of 15 minutes or less is recommended if the steady-state assumption is in doubt.

6.6.2   The Energy Budget Method

An equation expressing the partitioning of energy at the surface may be used in place of (6.6.5) when measurements of $\Delta\theta$ are not available[53, 54, 58]. The expression for the surface energy budget is:

$$H_0 \; + \; \lambda E \; = \; Q^* \; - G \tag{6.6.7}$$

where λE is the latent heat flux (λ is the latent heat of water vaporization and E is the evaporation rate), Q* is the net radiation and G the soil heat flux. $H_0 + \lambda E$ is the energy flux that is supplied to or extracted from the air, while Q* - G is the source or sink for this energy. Using $H_0 \; = \; -\rho C_p u_* \theta_*$, (6.6.7) can be written as:

$$\theta_* \; = \; \frac{\lambda E \; - \; Q^* \; + \; G}{\rho C_p u_*} \tag{6.6.8}$$

In this equation λE, Q* and G can be parameterized in terms of the total cloud cover N, the solar elevation ϕ, the air temperature T, the friction velocity u_* and θ_* itself. The idea is to use (6.6.8) to write θ_* as a function of the variables N, ϕ, T, and u_*:

$$\theta_* \; = \; f_2(N, \; \phi, \; T, \; u_*) \tag{6.6.9}$$

This equation then replaces (6.6.5). The further procedure of finding θ_* and u_* from (6.6.4) and (6.6.9) by iteration is similar to that used in the profile method.

6.6.3 Surface Roughness Length

The roughness length (z_0) is related to the roughness characteristics of the terrain. Under near-neutral conditions and with a homogeneous distribution of obstacles, a local value of z_0 can be determined from the logarithmic wind profile.

$$U(z) = \frac{u_*}{k} \ln(z/z_0) \qquad (6.6.10)$$

For general application, since typical landscapes almost always contain occasional obstructions, one should attempt to estimate an effective roughness length. The recommended method for estimating the effective roughness length is based on single level gustiness measurements σ_u [60]:

$$\frac{\sigma_u}{\overline{u}} = \frac{1}{\ln(z/z_0)} \qquad (6.6.11)$$

Wind measurements for use in (6.6.11) should be made between 20 z_0 and 100 z_0; to select the appropriate measurement level, an initial estimate of the effective roughness length must first be made based on a visual inspection of the landscape (see roughness classifications provided in Table 6-10). The sampling duration for σ_u and $\overline{u}$ should be between 3 and 60 minutes. Data collected for use in estimating the effective surface roughness should be stratified by wind speed (only data for wind speeds greater than 5 m/s should be used) and wind direction sector (using a minimum sector arc width of 30 degrees). Median z_0 values should be computed for each sector; results should then be inspected to determine whether the variation between sectors is significant. An average of the median values should be computed for adjacent sectors if the variation is not significant. Estimates of the effective surface roughness using these procedures are accurate to one significant figure; i.e., a computed value of 0.34 m should be rounded to 0.3 m. Documentation of the successful application of these procedures is provided in reference [61].

Table 6-10

Terrain Classification in Terms of Effective Surface Roughness Length, Z_0

Terrain Description	Z_0 (m)
Open sea, fetch at least 5 km	0.0002
Open flat terrain; grass, few isolated obstacles	0.03
Low crops, occasional large obstacles, $x'/h > 20$[*]	0.10
High crops, scattered obstacles, $15 < x'/h < 20$[*]	0.25
Parkland, bushes, numerous obstacles, x'/h 10[*]	0.50
Regular large obstacle coverage (suburb, forest)	0.50 - 1.0

[*] x' = typical distance to upwind obstacle; h = height of obstacle

6.6.4 Guidance for Measurements in the Surface Layer

Monin-Obukhov (M-O) similarity theory is strictly applicable to steady-state horizontally homogeneous conditions in the surface layer. The temperature and wind speed measurements for use with M-O theory should be representative of a layer that is both high enough to be above the influence of the individual surface roughness elements and yet low enough to be within the surface layer; as a rule of thumb, the measurements should be made within the layer from $20z_0$ to $100z_0$ above the surface (2 - 10 m for a surface roughness of 0.1 m) **[57]**.

Data quality objectives and, consequently, instrument specifications for monitoring of temperature and wind speed in the surface layer are determined by the limitations imposed during the extreme stability conditions; basically this requires a monitoring design with the capability to resolve the variable gradients in temperature and wind speed that can exist within the surface layer under various conditions.

The depth of the surface layer where M-O similarity theory applies ranges from about one tenth of the ABL depth (h) during neutral conditions (typically 500 - 600 m) to the lesser of $|L|$ or 0.1 h during non-neutral conditions (less than 10 m during extreme stability conditions). This variability in the depth of the surface layer imposes limitations on what can be accomplished with a single fixed set of sensors. To ensure the availability of measurements representative of the entire surface layer during all stability conditions, one should employ a tall-tower (60 m or taller) equipped with wind and temperature sensors at several levels including, as a minimum, 2, 10 and 60 m.   In the absence of a tall-tower, a standard 10-meter meteorological tower equipped with a single fixed set of sensors should be employed. Wind speed should be measured at the standard height of 10 m; the temperature difference should be measured between 2 and 10 m (for $z_0 \sim 0.1$ m). The usefulness of such a relatively low-lying measurement configuration lies in its applicability to both stable and unstable atmospheric conditions.

Application of M-O similarity should generally be restricted to low roughness sites located in relatively homogeneous terrain.   For such sites, the reliability of the profile method for estimating surface layer parameters is primarily dependent on accurate temperature difference measurements (see Section 3.2.2 for siting and exposure of temperature sensors and Section 5.1 for sensor specifications).

6.7   Use of Airport Data

Airport data refers to surface weather observations collected in support of various NWS and Federal Aviation Administration (FAA) programs; most, although not all, of the surface weather observation sites are located at airports. For practical purposes, because airport data are readily available, most regulatory modeling was initially performed using these data.   However, airport data do not meet this guidance - significant deviations include:

- The instruments used at airports are generally more robust and less sensitive than the instruments recommended in this guidance. For example, the thresholds for measuring wind direction and wind speed are higher than is recommended in this guidance; this results in a greater incidence of calms in airport data.

- Wind direction in airport data bases is reported to the nearest ten degrees - one degree resolution of wind direction is recommended in this guidance.

- Airport data for wind direction and wind speed are 2-minute averages; data for other variables, e.g., temperature and pressure are instantaneous readings - hourly averaging is recommended for all variables in this guidance.

Although data meeting this guidance are preferred, airport data continue to be acceptable for use in modeling. In fact observations of cloud cover and ceiling, data which traditionally have been provided by manual observation, are only available routinely in airport data; both of these variables are needed to calculate stability class using Turner's method (Section 6.4.1). The Guideline on Air Quality Models **[1]** recommends that modeling applications employing airport data be based on consecutive years of data from the most recent, readily available 5-year period. Airport data are available on the National Climatic Data Center (NCDC) World Wide Web site at http://www.ncdc.noaa.gov/. Documentation and guidance on NWS surface weather observations is provided in the Federal Meteorological Handbook No. 1 "Surface Weather Observations and Reports" **[62]**.

6.8   Treatment of Missing Data

Missing or invalid data should be flagged or replaced as appropriate depending on the model to be used. Note that the ISCST3 model recognizes specific flags for missing data; however, many models do not recognize flags and will not accept missing or invalid data. For use in these models, data bases with isolated one-hour gaps should be filled with estimates based on persistence or linear interpolation.   Application specific procedures should be used for filling longer gaps; guidance for developing such procedures is provided in Section 6.8.1. Substitutions for missing data should only be made to complete the data set for modeling applications; substitution should not be used to attain the 90% completeness requirement for regulatory modeling applications (Section 5.3.2).

6.8.1   Substitution Procedures

This section provides general guidance on substitution procedures for use in completing meteorological data bases prior to their use in modeling. It is intended for use by applicants and reviewing agencies in the development of substitution protocols for application to regulatory air quality dispersion modeling. Substitution protocols should be included in a modeling protocol and submitted for approval to the reviewing authority prior to the modeling analysis.

Substitution procedures will vary depending on the nature of the application, the availability of alternative sources of meteorological data, and the extent of the missing or invalid data. If the data base is such that there are relatively few isolated one-hour gaps, then an interpolation procedure, which is easily automated, may provide the most practical method of substitution. However, it there are lengthy periods with missing or invalid data, then application specific procedures will generally be necessary.

The goal of substitution should be to replace missing data with a "best estimate" so as to minimize the probable error of the estimate. The following suggestions have been prioritized in order of increasing probable error.

Substitution procedures which are considered to be "best estimators" include the following:

- Persistence - Persistence is the use of data from the previous time period (hour). This procedure is applicable for most meteorological variables for isolated one-hour gaps; caution should be used when the gaps occur during day/night transition periods.

- Interpolation - This procedure is applicable for most meteorological variables for isolated one-hour gaps and, depending on circumstances, may be used for more extended periods (several hours) for selected variables; e.g., temperature. As in the case of persistence, caution should be used when the gaps occur during day/night transition periods.

- Profiling - Profiling (profile extrapolation) refers to the procedure in which missing data for one level in a multi-level data base (e.g., data from a meteorological tower) is replaced by an estimate based on data from an alternative level or levels in the same data base. The probable error of the profiling estimate does not increase with the duration of the missing data, as is the case for persistence and interpolation. Consequently, profiling becomes a better estimator compared to persistence and interpolation as the length of the missing data period increases.   Profiling based on a power-law should be used for extrapolating wind speed with height; the stability dependent procedure discussed in Section 6.2.5 is recommended. Profiling based on lapse rate should be used for extrapolating temperature with height. Alternatively, with the approval of the reviewing authority, applicants may use site-specific profiling procedures for wind speed and temperature.

Substitution procedures which provide estimators with moderate probable error include the following:

- Substitution from sensors located at comparable levels at nearby locations with similar site-specific (surface-specific) characteristics.

- Persistence when used for more than several hours.

- Interpolation when used for more than several hours.

Substitution procedures which provide estimators with high probable error include the following:

- Substitution from measurements at nearby locations with dissimilar site-specific (surface-specific) characteristics.

- Substitution of a climatological value for a particular time period; e.g., a seasonal or monthly average.

- Substitution of simulated meteorology based, for example, on a boundary layer model.

- Substitution of "dummy data" such as a constant value for a variable.

6.9   Recommendations

The hourly scalar mean wind speed and wind direction should be used in steady-state Gaussian dispersion models. These statistics should be processed using the methods provided in Section 6.2.1; unit vector processing (Section 6.2.2) may also be used to estimate the hourly scalar mean wind direction. The standard deviation of the wind direction should be calculated using the techniques described in Section 6.2.1. Hourly statistics may be obtained by processing samples over an entire hour or by averaging sub-hourly statistics. The recommended sub-hourly averaging interval for wind data processing is 15 minutes; two valid 15-minute averages are required for a valid hourly average.

For the purposes of this guidance, a calm occurs when the wind speed is below the starting threshold of the anemometer or vane, whichever is greater. Calms require special treatment in such applications to avoid division by zero in the steady-state dispersion algorithm. For similar reasons, to avoid unrealistically high concentration estimates at low wind speeds (below the values used in validations of these models - about 1 m/s) EPA recommends that wind speeds less than 1 m/s be reset to 1 m/s for use in steady-state dispersion models; the unaltered data should be retained for use in non-steady-state modeling applications. Calms should be identified in processed data files by flagging the appropriate records; user's guides for the model being used should be consulted for model specific flagging conventions.

Recommended sampling and processing strategies for the primary meteorological variables for various applications are given in Table 6-1.

The Pasquill-Gifford (P-G) stability category should be determined with Turner's method (Section 6.4.1) using site-specific wind speed measurements at or near 10 m and representative

cloud cover and ceiling height. Other approved methods for estimating the P-G stability category, for use when representative cloud cover and ceiling observations are not available, include the solar radiation delta-T (SRDT) method described in Section 6.4.2, and turbulence-based methods using site-specific wind fluctuation statistics: σ_E (Section 6.4.3) or σ_A (Section 6.4.4). Alternative methods for determining stability category should be evaluated in consultation with the Regional Office.

Emperical relationships for use in models employing boundary layer scaling techniques should be selected in accordance with a von Karmam constant of 0.4; recmmended emperical relationships are given in reference [59].

Missing data should be flagged or replaced as appropriate depending on the model to be used. Isolated one-hour gaps in meteorological data bases used in regulatory modeling should be filled with estimates bases on persistence or interpolation. Application specific procedures should be used to fill longer gaps

If the recommendations in this section cannot be achieved, then alternative approaches should be developed in consultation with the EPA Regional Office.

7. DATA REPORTING AND ARCHIVING

Meteorological data collected for use in regulatory modeling applications should be made available to the regulatory agency as necessary. In some cases, as part of an oversight function, agencies may require periodic or even real-time access to the data as it is being collected. The regulatory agency may, in addition, require long-term archival of meteorological data bases used in some applications [e.g., analyses supporting State Implementation Plan (SIP) actions and Prevention of Significant deterioration (PSD) permits]. Procedures for compliance with such requirements should be worked out with the agency and documented in the monitoring protocol prior to commencement of monitoring.

7.1   Data Reports

The following general recommendations apply to meteorological data bases being prepared for use in regulatory modeling applications. All meteorological data should be reduced to hourly averages using the procedures provided in Section 6. The data should be recorded in chronological order; records should be labeled according to the observation time (defined as the time at the end of the averaging period; i.e., the hour ending).   If possible, each data record should contain the data for one hourly observation (one record per hour). The first four fields of each data record should identify the year, month, day and hour of the observation. The data records should be preceded by a header record providing the following information:

- Station name

- Station location (latitude, longitude, and time zone)

- Station elevation

- Period of record and number of records

- Validation level (see Section 8)

A summary report should accompany each meteorological data base prepared for use in regulatory modeling applications. The summary report should provide the following information:

- number and percent of hours with complete/valid data.

- number and percent of hours with valid stability data.

- number and percent of hours with valid wind speed and wind direction data including valid calms.

- list of hours requiring substitutions including identification of the missing variable and the substitution protocol employed.

7.2   Data Archives

Meteorological data used in support of some regulatory actions (e.g, SIP revisions and PSD permit applications) may be needed in support of continuing actions for these regulations and, consequently should be archived by the agency with permit granting authority; normally the State.   Such an archive should be designed for the data actually used in the regulatory application - i.e., the processed data, but may also include some raw data. Archival of other raw data is at the discretion of the applicant. The processed meteorological data should be archived initially for one year with provisions for review and extension to five years, ten years, or indefinite. Where data were originally reduced from strip chart records, the charts should also be archived. Original strip chart records should be retained for a minimum of five years. If an archive is to be eliminated, an attempt should be made to contact potential user's who might be affected by such an action.

7.3   Recommendations

Procedures for compliance with reporting and archiving requirements should be worked out with the agency and documented in the monitoring protocol prior to commencement of monitoring.

Meteorological data provided to regulatory agencies for use in modeling should be reduced to hourly averages using the procedures provided in Section 6. The data should be recorded in chronological order; records should be labeled according to the observation time (defined as the time at the end of the averaging period; i.e., the hour ending).

Meteorological data used in support of SIP revisions or PSD permit applications should be archived initially for one year with provisions for review and extension to five years, ten years, or indefinite.

8. QUALITY ASSURANCE AND QUALITY CONTROL

Quality Assurance/Quality Control (QAQC) procedures are required to ensure that the data collected meet standards of reliability and accuracy (see Section 5.1). Quality Control (QC) is defined as those operational procedures that will be routinely followed during the normal operation of the monitoring system to ensure that a measurement process is working properly. These procedures include periodic calibration of the instruments, site inspections, data screening, data validation, and preventive maintenance. The QC procedures should produce quantitative documentation to support claims of accuracy. Quality Assurance (QA) is defined as those procedures that will be performed on a more occasional basis to provide assurance that the measurement process is producing data that meets the data quality objectives (DQO). These procedures include routine evaluation of how the QC procedures are implemented (system audits) and assessments of instrument performance (performance audits).

The QAQC procedures should be documented in a Quality Assurance Project Plan (QAPP) and should include a "sign-off" by the appropriate project or organizational authority. The QAPP should include the following [63]:

1. Project description - how meteorology is to be used

2. Project organization - how data validity is supported

3. QA objective - how QA will document validity claims

4. Calibration method and frequency - for meteorology

5. Data flow - from samples to archived valid values

6. Validation and reporting methods - for meteorology

7. Audits - performance and system

8. Preventive maintenance

9. Procedures to implement QA objectives - details

10. Management support - corrective action and reports

It is important that the person providing the QA be independent of the organization responsible for the collection of the data and the maintenance of the measurement systems. Ideally, this person should be employed by an independent company. There should not be any lines of intimidation available to the operators which might be used to influence the QA audit report and actions. With identical goals of valid data, the QA person should encourage the operator to use the same methods the QA person uses (presumably these are the most comprehensive methods) when challenging the measurement system during a performance audit. When this is done, the QA task reduces to spot checks of performance and examination of records thus providing the best data with the best documentation at the least cost.

8.1   Instrument Procurement

The specifications required for the applications for which the data will be used (see Sections 5.0 and 6.0) along with the test method to be used to determine conformance with the specification should be a part of the procurement document. A good QA Plan will require a QA sign-off of the procurement document for an instrument system containing critical requirements. An instrument should not be selected solely on the basis of price and a vague description, without detailed documentation of sensor performance.

8.1.1   Wind Speed

This section provides guidance for procurement of anemometers (i.e., mechanical wind speed sensors employing cups or vane-oriented propellers) which rely on the force of the wind to turn a shaft. Guidance for the procurement of remote sensors for the measurement of wind speed is provided in Section 9. Other types of wind speed sensors (e.g., hot wire anemometers and sonic anemometers) are not commonly used for routine monitoring and are beyond the scope of this guide. An example performance specification for an anemometer is shown in Table 8-1.

Table 8-1

Example Performance Specification for an Anemometer

Range	0.5 m/s to 50 m/s
Threshold[1]	$\leq$ 0.5 m/s
Accuracy (error)[1,2]	$\leq$ (0.2 m/s + 5% of observed)
Distance Constant[1]	$\leq$ 5 m at 1.2 kg/m^3 (at std sea-level density)

[1] As determined by wind tunnel test conducted on production samples in accordance with ASTM D-22.11 test methods

[2] aerodynamic shape (cup or propeller) with permanent serial number to be accompanied by test report, traceable to NBS, showing rate of rotation vs. wind speed at 10 speeds.

The procurement document should ask for (1) the starting torque of the anemometer shaft (with cup or propeller removed) which represents a new bearing condition, and (2) the starting torque above which the anemometer will be out of specification.; when the latter value is exceeded, the bearings should be replaced.

The ASTM test cited above includes a measurement of off-axis response. Some anemometer designs exhibit errors greater than the accuracy specification with off-axis angles of as little as 10 degrees. However, there is no performance specification for this type of error at this time, due to a lack of sufficient data to define what the specification should be.

8.1.2 Wind Direction

This section provides guidance for procurement of wind vanes; i.e., mechanical wind direction sensors which rely on the force of the wind to turn a shaft. Guidance for the procurement of remote sensors for the measurement of wind direction is provided in Section 9.

The wind direction measurement with a wind vane is a relative measurement with respect to the orientation of the direction sensor. There are three parts to this measurement which must be considered in quality assurance. These are: (l) the relative accuracy of the vane performance in converting position to output, (2) the orientation of the vane both horizontal (with respect to "true north") and vertical (with respect to a level plane), and (3) the dynamic response of the vane and conditioning circuit to changes in wind direction.

The procurement document should ask for: (1) the starting torque of the vane shaft (with the vane removed) which represents a new bearing (and potentiometer) condition, and (2) the starting torque above which the vane will be out of specification.; when the latter value is exceeded, the bearings should be replaced. An example performance specification for a wind vane is shown in Table 8-2.

Table 8-2

Example Performance Specification for a Wind Vane

Range	1 to 360 or 540 degrees
Threshold[1]	$\leq$ 0.5 m/s
Accuracy (error)[1]	$\leq$ 3 degrees relative to sensor mount or index
	$\leq$ 5 degrees absolute error for installed system
Delay Distance[1]	$\leq$ 5 m at 1.2 kg/m^3 (at std sea-level density)
Damping Ratio[1]	$\geq$ 0.4 at 1.2 kg/m^3 or
Overshoot[1]	$\leq$ 25% at 1.2 kg/m^3

[1] As determined by wind tunnel test conducted on production samples in accordance with ASTM D-22.11 test methods

The range of 1 to 540 degrees was originally conceived to minimize strip chart "painting" when the direction varied around 360 degrees. It also minimizes errors (but does not eliminate them) when sigma meters are used. It may also provide a means of avoiding some of the "dead band" errors from a single potentiometer. In these days of "smart" data loggers, it is possible to use a single potentiometer (1 to 360 degree) system without excessive errors for either average direction or σ_A.

If the wind direction samples are to be used for the calculation of σ_A, the specification should also include a time constant requirement for the signal conditioner. Direction samples should be effectively instantaneous. At 5 m/s, a 1m delay distance represents 0.2 seconds. A signal conditioner specification of a time constant of <0.2 seconds would insure that the σ_A value was not attenuated by an averaging circuit provided for another purpose.

8.1.3 Temperature and Temperature Difference

When both temperature and differential temperature are required, it is important to specify both accuracy and relative accuracy (not to be confused with precision or resolution). Accuracy is performance compared to truth, usually provided by some standard instrument in a controlled environment. Relative accuracy is the performance of two or more sensors, with respect to one of the sensors or the average of all sensors, in various controlled environments. A temperature sensor specification might read:

Range	-40 to +60 °C.
Accuracy (error)	≤ 0.5 °C.

A temperature difference specification might read:

Range	-5 to +15 °C.
Relative accuracy (error)	≤ 0.1 °C.

While calibrations and audits of both accuracy and relative accuracy are usually conducted in controlled environments, the measurement is made in the atmosphere. The greatest source of error is usually solar radiation. Solar radiation shield specification is therefore an important part of the system specification. Motor aspirated radiation shields (and possibly high performance naturally ventilated shields) will satisfy the less critical temperature measurement. For temperature difference, it is critical that the same design motor aspirated shield be used for both sensors. The expectation is that the errors from radiation (likely to exceed 0.2 °C) will zero out in the differential measurement. A motor aspirated radiation shield specification might read:

Radiation range	-100 to 1300 W/m^2
Flow rate	3 m/s or greater
Radiation error	< 0.2 °C.

8.1.4   Dew Point Temperature

Sensors for measuring dew point temperature can be particularly susceptible to precipitation, wind, and radiation effects. Therefore, care should be taken in obtaining proper (manufacturer-recommended) shielding and aspiration equipment for the sensors. If both temperature and dew point are to be measured, aspirators can be purchased which will house both sensors. If measurements will be taken in polluted atmospheres, gold wire electrodes will minimize corrosion problems. For cooled mirror sensors consideration should be given to the susceptibility of the mirror surface to contamination.

8.1.5   Precipitation

For areas where precipitation falls in a frozen form, consideration should be given to ordering an electrically heated rain and snow gauge. AC power must be available to the precipitation measurement site. For remote sites where AC power is not available, propane-heated gauges can be ordered. However, if air quality measurements are being made at the same location, consideration should be given to the air pollutant emissions in the propane burner exhaust.

Air movement across the top of a gauge can affect the amount of catch. For example, Weiss [64] reports that at a wind speed of 5 mph, the collection efficiency of an unshielded gauge decreased by 25%, and at 10 mph, the efficiency of the gauge decreased by 40%. Therefore, it is recommended that all precipitation gauges be installed with an Alter-type wind screen, except in locations where frozen precipitation does not occur.

Exposure is very important for precipitation gauges; the distance to nearby structures should be at least two to four times the height of the structures (see Section 3.1.3). Adequate lengths of cabling must be ordered to span the separation distance of the gauge from the data acquisition system. If a weighing gauge will be employed, a set of calibration weights should be obtained.

8.1.6   Pressure

The barometric pressure sensor should normally have a proportional and linear electrical output signal for data recording. Alternately, a microbarograph can be used with a mechanical recording system. Some barometers operate only within certain pressure ranges; for these, care should be taken that the pressure range is appropriate for the elevation of the site where measurements will be taken.

8.1.7   Radiation

Radiation instruments should be selected from commercially available and field-proven systems. These sensors generally have a low output signal, so that they should be carefully matched with the signal conditioner and data acquisition system. Another consideration in the

selection of data recording equipment is the fact that net radiometers have both positive and negative voltage output signals.

8.2   Installation and Acceptance Testing

The installation period is the optimal time to receive appropriate training in instrument principles, operations, maintenance, and troubleshooting, as well as data interpretation and validation. Meteorological consultants as well as some manufacturers and vendors of meteorological instruments provide these services.

An acceptance test is used to determine if an instrument performs according to the manufacturer's specifications [2]. Manufacturer's procedures for unpacking, inspection, installation, and system diagnostics should be followed to assure that all components are functioning appropriately. All acceptance-testing activities should be documented in the station log.

8.2.1   Wind Speed

This section provides guidance for the acceptance testing of anemometers (i.e., mechanical wind speed sensors employing cups or vane-oriented propellers) which rely on the force of the wind to turn a shaft. Guidance for the acceptance testing of remote sensors for the measurement of wind speed is provided in Section 9. Other types of wind speed sensors (e.g., hot wire anemometers and sonic anemometers) are not commonly used for routine monitoring and are beyond the scope of this guide.

A technical acceptance test may serve two purposes. First, it can verify that the instrument performs as the manufacturer claims, assuming the threshold, distance constant and transfer function (rate of rotation vs. wind speed) are correct. This test catches shipping damage, incorrect circuit adjustments, poor workmanship, or poor QA by the manufacturer. This level of testing should be equivalent to a field performance audit. The measurement system is challenged with various rates of rotation on the anemometer shaft to test the performance from the transducer in the sensor to the output. The starting torque of the bearing assembly is measured and compared to the range of values provided by the manufacturer (new and replacement).

The other purpose of a technical acceptance test is to determine if the manufacturer really has an instrument which will meet the specification. This action requires a wind tunnel test. The results would be used to reject the instrument if the tests showed failure to comply. An independent test laboratory is recommended for conducting the ASTM method test.

The specification most likely to fail for a low cost anemometer is threshold, if bushings are used rather than quality bearings. A bushing design may degrade in time faster than a well designed bearing assembly and the consequence of a failed bushing may be the replacement of the whole anemometer rather than replacement of a bearing for a higher quality sensor. A receiving inspection cannot protect against this problem. A mean-time-between-failure

specification tied to a starting threshold torque test is the only reasonable way to assure quality instruments if quality brand names and model numbers cannot be required.

8.2.2   Wind Direction

This section provides guidance for the acceptance testing of wind vanes; i.e., mechanical wind direction sensors which rely on the force of the wind to turn a shaft. Guidance for the acceptance testing of remote sensors for the measurement of wind direction is provided in Section 9.

A technical acceptance test can verify the relative direction accuracy of the wind vane by employing either simple fixtures or targets within a room established by sighting along a 30-60-90 triangle. There is no acceptance test for sighting or orientation, unless the manufacturer supplies an orientation fixture and claims that the sensor is set at the factory to a particular angle (180 degrees for example) with respect to the fixture.

If σ_A is to be calculated from direction output samples, the time constant of the output to an instantaneous change should be estimated. If the direction output does not change as fast as a test meter on the output can react, the time constant is too long.

If σ_A is calculated by the system, a receiving test should be devised to check its performance. The manual for the system should describe tests suitable for this challenge.

8.2.3   Temperature and Temperature Difference

The simplest acceptance test for temperature and temperature difference would be a two point test, room temperature and a stirred ice slurry. A reasonably good mercury-in-glass thermometer with some calibration pedigree can be used to verify agreement to within l °C. It is important to stir the liquid to avoid local gradients. It should not be assumed that a temperature difference pair will read zero when being aspirated in a room. If care is taken that the air drawn into each of the shields comes from the same well mixed source, a zero reading might be expected.

A second benefit of removing the transducers from the shields for an acceptance test comes to the field calibrator and auditor. Some designs are hard to remove and have short leads. These conditions can be either corrected or noted when the attempt is first made in the less hostile environment of a receiving space.

8.2.4   Dew Point Temperature

A dew point temperature acceptance test at one point inside a building, where the rest of the system is being tested, will provide assurance that connections are correct and that the operating circuits are functioning. The dew point temperature for this test should be measured with a wet-dry psychrometer (Assman type if possible) or some other device in which some measure of accuracy is documented. If it is convenient to get a second point outside the building,

assuming that the dew point temperature is different outside (usually true if the building is air conditioned with water removed or added), further confidence in the performance is possible. Of course, the manufacturer's methods for checking parts of the system (see the manual) should also be exercised.

8.2.5   Precipitation

The receiving inspection for a precipitation gauge is straightforward. With the sensor connected to the system, check its response to water (or equivalent weight for weighing gauges) being introduced into the collector. For tipping bucket types, be sure that the rate is less than the equivalent of one inch (25mm) per hour if the accuracy check is being recorded. See the section on calibration (8.3) for further guidance.

8.2.6   Pressure

A check inside the building is adequate for an acceptance test of atmospheric pressure. An aneroid barometer which has been set to agree with the National Weather Service (NWS) equivalent sea-level pressure can be used for comparison. If station pressure is to be recorded by the pressure sensor, be sure that the aneroid is set to agree with the NWS station pressure and not the pressure broadcast on radio or television. A trip to the NWS office may be necessary to set the aneroid for this agreement since the station pressure is sensitive to elevation and the NWS office may be at a different elevation than the receiving location.

8.2.7   Radiation

A simple functional test of a pyranometer or solarimeter can be conducted with an electrical light bulb. With the sensor connected to the system as it will be in the field, cover it completely with a box with all cracks taped with an opaque tape. Any light can bias a "zero" check. The output should be zero. Do not make any adjustments without being absolutely sure the box shields the sensor from any direct, reflected, or diffuse light. Once the zero is recorded, remove the box and bring a bulb (100 watt or similar) near the sensor. Note the output change. This only proves that the wires are connected properly and the sensor is sensitive to light.

If a net radiometer is being checked, the bulb on the bottom should induce a negative output and on the top a positive output. A "zero" for a net radiometer is much harder to simulate. The sensor will (or may) detect correctly a colder temperature on the bottom of the shielding box than the top, which may be heated by the light fixtures in the room. Check the manufacturer's manual for guidance.

8.3   Routine Calibrations

A calibration involves measuring the conformance to or discrepancy from a specification for an instrument and an adjustment of the instrument to conform to the specification.

Documentation of all calibrations should include a description of the system "as found", details of any adjustments to the instrument, and a description of the system "as left"; this documentation is a vital part of the "paper-trail" for any claims of data validity. Calibrations are often confused with performance audits since both involve measuring the conformance of an instrument to a specification; the main difference has to do with the independence of the person performing the audit or calibration - the performance audit should be conducted by a person who is independent of the operating organization - calibrations, on the other hand, are often performed by individuals within the operating organization. Guidance specific to performance audits is provided in Section 8.4.

The guidance provided on calibration procedures in the following applies to in situ meteorological sensors such as would be mounted on a tower (e.g., wind vanes and anemometers) or located at ground level (e.g., a solar radiation sensor). Ideally, a calibration should be performed in an environment as close as possible to laboratory bench-test as conditions allow. For tower mounted sensors this usually involves removing the sensor from tower. The alternative to a bench-test calibration of the in situ sensor is a calibration using a collocated transfer standard; this involves locating an identical standard instrument as close as practical to the instrument being calibrated. The collocated standard transfer method is the most complete calibration/audit method from the standpoint of assessing total system error. However it has two serious drawbacks: 1) it is limited to the conditions that prevailed during the calibration/audit, and 2) it is sensitive to siting and exposure bias.

Calibrations using a bench test or collocated transfer standard are not generally applicable to the upper-air measurement systems; the special procedures required for calibrations and audits of upper-air measurement systems are discussed in Section 9.

Documentation supplied with newly purchased instruments should include the manufacturer's recommended calibration procedures. The guidance on calibration procedures provided in the following is intended to supplement the manufacturer's recommendations; when in doubt, the instrument manufacturer should be consulted.

8.3.1   Sensor Check

There are three types of action which can be considered a sensor check. First, one can look at and perform "housekeeping" services for the sensors. Secondly, one can measure some attribute of the sensor to detect deterioration in anticipation of preventative maintenance. Thirdly, the sensor can be subjected to a known condition whose consequence is predictable through the entire measurement system, including the sensor transducer. Each of these will be addressed for each variable, where appropriate, within the divisions of physical inspection and measurement and accuracy check with known input.

8.3.1.1 Physical inspection

The first level of inspection is visual. The anemometer and vane can be looked at, either directly or through binoculars or a telescope, to check for physical damage or signs of erratic

behavior. Temperature shields can be checked for cleanliness. Precipitation gauges can be inspected for foreign matter which might effect performance. The static port for the atmospheric pressure system also can be examined for foreign matter. Solar radiation sensors should be wiped clean at every opportunity.

A better level of physical inspection is a "hands on" check. An experienced technician can feel the condition of the anemometer bearing assembly and know whether or not they are in good condition. This is best done with the aerodynamic shape (cup wheel, propeller, or vane) removed. Caution: Damage to anemometers and vanes is more likely to result from human handling than from the forces of the wind, especially during removal or installation and transport up and down a tower. The proper level of aspiration through a forced aspiration shield can be felt and heard under calm condition.

The best level of sensor check is a measurement. The anemometer and wind vane sensors have bearings which will certainly degrade in time. The goal is to change the bearings or the sensors before the instrument falls below operating specifications. Measurements of starting torque will provide the objective data upon which maintenance decisions can be made and defended. The presence, in routine calibration reports, of starting torque measurements will support the claim for valid data, if the values are less than the replacement torques.

The anemometer, identified by the serial number of the aerodynamic shape, should have a wind tunnel calibration report (see Section 8.1) in a permanent record folder. This is the authority for the transfer function (rate of rotation to wind speed) to be used in the next section. The temperature transducers, identified by serial number, should have calibration reports showing their conformity for at least three points to their generic transfer function (resistance to temperature, usually). These reports should specify the instruments used for the calibration and the method by which the instruments are tied to national standards (NBS). The less important sensors for solar radiation and atmospheric pressure can be qualified during an audit for accuracy.

8.3.1.2 Accuracy check with known input

Two simple tests will determine the condition of the anemometer (assuming no damage is found by the physical inspection). The aerodynamic shape must be removed. The shaft is driven at three known rates of rotation. The rates are known by independently counting shaft revolutions over a measured period of time in synchronization with the measurement system timing. The rates should be meaningful such as the equivalent of 2 m/s, 5 m/s and 10 m/s. Conversion of rates of rotation to wind speed is done with the manufacturer's transfer function or wind tunnel data. For example, if the transfer function is m/s = 1.412 r/s + 0.223, then rates of rotation of 1.3, 3.4 and 6.9 revolutions per second (r/s) would be equivalent to about 2, 5 and 10 m/s. All that is being tested is the implementation of the transfer function by the measuring system. The output should agree within one increment of resolution (probably 0.1 m/s). If problems are found, they might be in the transducer, although failures there are usually catastrophic. The likely source of trouble is the measurement system (signal conditioner, transmitting system, averaging system and recording system).

The second test is for starting torque. This test requires a torque watch or similar device capable of measuring in the range of 0.1 to 10 gm-cm depending upon the specifications provided by the manufacturer.

A successful response to these two tests will document the fact that the anemometer is operating as well as it did at receiving inspection, having verified threshold and accuracy. Changes in distance constant are not likely unless the anemometer design has changed. If a plastic cup is replaced by a stainless steel cup, for example, both the transfer function and the distance constant will likely be different. The distance constant will vary as the inverse of the air density. If a sea-level distance constant is 3.0 m, it may increase to 3.5 m in Denver and 4.3 m at the mountain passes in the Rockies.

For wind direction, a fixture holding the vane, or vane substitute, in positions with a known angle change is a fundamental challenge to the relative accuracy of the wind vane. With this method, applying the appropriate strategy for 360 or 540 degree systems, the accuracy of the sensor can be documented. The accuracy of the wind direction measurement, however, also depends on the orientation of the sensor with respect to true north.

The bearing to distant objects may be determined by several methods. The recommended method employs a solar observation (see Reference 3, p.11) to find the true north-south line where it passes through the sensor mounting location. Simple azimuth sighting devices can be used to find the bearing of some distant object with respect to the north-south line. The "as found" and "as left" orientation readings should report the direction to or from that distant object. The object should be one toward which the vane can be easily aimed and not likely to become hidden by vegetation or construction.

There are two parts of most direction vanes which wear out. One part is the bearing assembly and the other is the transducer, usually a potentiometer. Both contribute to the starting torque and hence the threshold of the sensor. A starting torque measurement will document the degradation of the threshold and flag the need for preventive maintenance. An analog voltmeter or oscilloscope is required to see the noise level of a potentiometer. Transducer noise may not be a serious problem with average values but it is likely to have a profound effect on σ_A.

The dynamic performance characteristics of a wind vane are best measured with a wind tunnel test. A generic test of a design sample is adequate. As with the anemometer, the dynamic response characteristics (threshold, delay distance and damping ratio) are density dependent.

Temperature transducers are reasonably stable, but they may drift with time. The known input for a temperature transducer is a stable thermal mass whose temperature is known by a standard transducer. The ideal thermal mass is one with a time constant on the order of an hour in which there are no thermal sources or sinks to establish local gradients within the mass. It is far more important to know what a mass temperature is than to be able to set a mass to a particular temperature.

For temperature difference systems, the immersion of all transducers in a single mass as described above will provide a zero-difference challenge accurate to about 0.01 °C. When this test is repeated with the mass at two more temperatures, the transducers will have been challenged with respect to how well they are matched and how well they follow the generic

transfer function. Mass temperatures in the ranges of 0 to 10 °C, 15 to 25 °C, and 30 to 40 °C are recommended. A maximum difference among the three temperatures (i.e., 0, 20, and 40 °C) is optimum. Once the match has been verified, known resistances can be substituted for the transducers representing temperatures, according to the generic transfer function, selected to produce known temperature difference signals to the signal conditioning circuitry. This known input will challenge the circuitry for the differential measurement.

Precipitation sensors can be challenged by inserting a measured amount of water, at various reasonable rainfall rates such as 25 mm or less per hour. The area of the collector can be measured to calculate the amount of equivalent rainfall which was inserted. The total challenge should be sufficient to verify a 10% accuracy in measurement of water. This does not provide information about errors from siting problems or wind effects.

Dew point temperature (or relative humidity), atmospheric pressure and radiation are most simply challenged in an ambient condition with a collocated transfer standard. An Assmann psychrometer may be used for dew point. An aneroid barometer checked against a local National Weather Service instrument is recommended for atmospheric pressure. Another radiation sensor with some pedigree or manufacturer's certification may be used for pyranometers and net radiometers. A complete opaque cover will provide a zero check.

8.3.2   Signal Conditioner and Recorder Check

For routine calibration of measurement circuits and recorders, use the manufacturer's recommendations. The outputs required by the test described in 8.3.1.2 must be reflected in the recorded values. Wind speed is used as an example in this section. Other variables will have different units and different sensitivities but the principle is the same. For sub-system checks, use the manual for specific guidance.

8.3.2.1 Analog system

Some systems contain "calibration" switches which are designed to test the stability of the circuits and to provide a basis for adjustment if changes occur. These should certainly be exercised during routine calibrations when data loss is expected because of calibration. In the hierarchy of calibrations, wind tunnel is first, known rate of rotation is second, substitute frequency is third and substitute voltage is fourth. The "calibration" switch is either third or fourth.

If analog strip chart recorders are used, they should be treated as separate but vital parts of the measurement system. They simply convert voltage or current to a mark on a time scale printed on a continuous strip of paper or composite material. The output voltage or current of the signal conditioner must be measured with a calibrated meter during the rate of rotation challenge. A simple transfer function, such as 10 m/s per volt, will provide verification of the measurement circuit at the output voltage position. The recorder can be challenged separately by inputting known voltages and reading the mark on the scale, or by noting the mark position when the rate

of rotation and output voltage are both known. See the recorder manual for recommendations should problems arise.

This special concern with recorders results from the variety of problems which analog recorders can introduce. A good measurement system can be degraded by an inappropriate recorder selection. If resolution is inadequate to distinguish between 1.3 m/s and 1.5 m/s, a 0.2 m/s accuracy is impossible. If enough resolution is just barely there, changes in paper as a function of relative humidity and changes in paper position as it passes the marking pen and excessive pen weight on the paper can be the limit of accuracy in the measurement. If the strip chart recorder is used only as a monitor and not as a backup for the primary system, its accuracy is of much less importance. The recorder from which data are recovered for archiving is the only recorder subject to measurement accuracy specifications.

8.3.2.2 Digital system

A digital system may also present a variety of concerns to the calibration method. One extreme is the digital system which counts revolutions or pulses directly from the sensor. No signal conditioning is used. All that happens is controlled by the software of the digital system and the capability of its input hardware to detect sensor pulses and only sensor pulses. The same challenge as described in 8.3.1.2 is used. The transfer function used to change rate of rotation to m/s should be found in the digital software and found to be the same as specified by the manufacturer or wind tunnel test. If any difference is found between the speed calculated from the known number of revolutions in the synchronous time period and the speed recorded in the digital recorder, a pulse detection problem is certain. A receiving inspection test may not uncover interference pulses which exist at the measurement site. For solution of this type of problem, see the digital recorder manufacturer's manual or recommendations.

A digital data logger may present different concerns. It may be a device which samples voltages, averages them, and transfers the average to a memory peripheral, either at the site or at the end of a communication link. Conversion to engineering units may occur at almost any point. The routine calibration should look at the output voltage of a signal conditioner as a primary point to assess accuracy of measurement. Analog to digital conversion, averaging and transmission and storage would be expected to degrade the measurement accuracy very little. Such functions should contribute less than 0.05 m/s uncertainty from a voltage input to a stored average value. If greater errors are found when comparing known rates of rotation and known signal conditioning output voltages to stored average wind speed values, check the data logger manual for specifications and trouble-shooting recommendations.

8.3.3   Calibration Data Logs

Site log books must record at least the following:

- Date and time of the calibration period (no valid data)

- Name of calibration person or team members

- Calibration method used (this should identify SOP number and data sheet used)

- Where the data sheet or sheets can be found on site

- Action taken and/or recommended

The data sheet should contain this same information along with the measurement values found and observations made. Model and serial numbers of equipment tested and used for testing must appear. The original report should always be found at the site location and a copy can be used for reports to management (a single-copy carbon form could be used). The truism that "it is impossible to have too many field notes" should be underscored in all training classes for operators and auditors.

8.3.4 Calibration Report

The calibration report may be as simple as copies of the calibration forms with a cover page, summary and recommendations. While the calibration forms kept at the site provide the basis for the operator or the auditor to trace the performance of the instrument system, the copies which become a part of the calibration report provide the basis for management action should such be necessary. The calibration report should travel from the person making out the report through the meteorologist responsible for the determination of data validity to the management person responsible for the project. Any problem should be highlighted with an action recommendation and a schedule for correction. As soon as the responsible management person sees this report the responsibility for correction moves to management, where budget control usually resides. A signature block should be used to document the flow of this information.

8.3.5 Calibration Schedule/Frequency

System calibration and diagnostic checks should be performed at six month intervals, or in accordance with manufacturer's recommendations, whichever is more frequent. The risk of losing data increases with the interval between operational checks. To reduce this risk, routine operational checks should be performed on a daily basis; these daily checks may be performed remotely. On-site inspections and maintenance should be performed on a weekly basis.

8.3.6 Data Correction Based on Calibration Results

Corrections to the raw data are to be avoided. A thorough documentation of an error clearly defined may result in the correction of data (permanently flagged as corrected). For example, if an operator changes the transfer function in a digital logger program and it is subtle enough not to be detected in the quality control inspection of the data stream, but is found at the next calibration, the data may be corrected. The correction can be calculated from the erroneous transfer function and applied to the period starting when the logger program was changed (determined by some objective method such as a log entry) and ending when the error was found and corrected.

Another example might be a damaged anemometer cup or propeller. If an analysis of the data points to the time when the damage occurred, a correction period can be determined. A wind tunnel test will be required to find a new transfer function for the damaged cup or propeller assembly. With the new transfer function defining the true speed responsible for a rate of rotation, and with the assumption that the average period is correctly represented by a steady rate of rotation, a correction can be made and flagged. This is a more risky example and judgment is required since the new transfer function may be grossly different and perhaps non-linear.

8.4   Audits

The audit function has two components, the system audit (in essence, a challenge to the QAPP) and the performance audit (a challenge to the individual measurement systems).

The system audit provides an overall assessment of the commitment to data validity; as such, all commitments made in the QAPP should be subject to challenge. Typical questions asked in the systems audit include: "are standard operating procedures being followed?", "is the station log complete and up-to-date?" All deficiencies should be recorded in the audit report along with an assessment of the likely effect on data quality. Corrective actions related to a systems audit should be obvious if the appropriate questions are asked.

The performance audit is similar to a calibration in terms of the types of activities performed (Section 8.3) - all the performance audit adds is an independent assurance that the calibrations are done correctly and that the documentation is complete and accurate. In the ideal case, when both the auditor and site operator are equally knowledgeable, the auditor functions as an observer while the site operator performs the calibration; in this instance the auditor functions in a "hands-off" mode. In initial audits, since newly hired site operators may have little or no experience with meteorological instruments, the hands-off approach may not be practical or desirable. In these instances, the audit may also function as a training exercise for the site operator.

8.4.1   Audit Schedule and Frequency

An initial audit should be performed within 30 days of the start-up date for the monitoring program. The 30-day period is a compromise between the need for early detection and correction of deficiencies and the time needed for shake-down and training. Follow-up audits should be conducted at six-month intervals.

8.4.2   Audit Procedure

To ensure against conflicts of interest, all audits should be conducted by individuals who are independent of the organizations responsible for the monitoring and/or using the data. This is especially important as the audit will be essential in any legal claims related to data validity. The audit should begin with a briefing stating the goals of the audit and the procedures to be employed - in addition, if any assistance is needed (e.g., in removing a wind vane from a tower)

this would be the time to arrange such with the site technicians. An exit interview should be conducted when the audit is finished; management from the organizations involved should be present at both the initial briefing and the exit interview.

8.4.3 Corrective Action and Reporting

A corrective action program is an essential management tool for coordination of the QAQC process. Activities associated with the corrective action program include: review of procedures for reporting deficiencies, problem tracking, planning and implementing measures to correct problems, and tracking of problem resolution. Documentation of corrective actions is included with other information in support of data validity. A sample form for documenting corrective actions can be found in reference **[65]**.

An audit report should be completed and submitted within 30 days of the audit performance. This is an important document in that it provides a basis for any legal claims to data validity. As such, care should be taken to ensure that all statements related to data validity are supportable. Where possible the report should contain copies of the forms used in the audit.

8.5 Routine and Preventive Maintenance

Data quality is dependent on the care taken in routine and preventative maintenance. These functions are the responsibility of the site technicians; given their important QAQC role, they should be fully trained to maintain the equipment. The training program for the site technicians should be addressed in the QAPP. The following additional information on maintenance should also be included in the QAPP:

- A list the site technicians and their alternates

- Procedures and checklists for preventive maintenance

- Schedule for preventive maintenance

- Procedures for maintaining spare components

- A list of the components to be checked and/or replaced

Checklists are an essential component of a routine maintenance program and should be used as a matter of course. The instrument manuals should be used as the starting point for the checklist for each of instruments - a good manual should indicate what components need to be checked and how often. A station checklist should also be developed; this should include the following:

- A List of safety and emergency equipment.

- List of items to be inspected following severe weather.

- A checkoff to ensure there is adequate disk space for on-site storage of the raw data.

- A checkoff to indicate that backup of data has been completed.

- A checkoff to indicate that clocks have been checked and adjusted as necessary.

- A checkoff for the cables and guy wires securing the equipment.

All routine and preventive maintenance activities should be recorded in the station log and/or on the appropriate checklist. The station log and checklist provide the necessary paper trail to support claims of accuracy.

8.5.1   Standard Operating Procedures

Standard operating procedures (SOPs) should be developed that are specific to the operations at a given site. The purpose of an SOP is to spell out operating and QC procedures with the ultimate goal of maximizing data quality and data capture rates. Operations should be performed according to a set of well defined, written SOPs with all actions documented in logs and on prepared forms. SOPs should be written in such a way that if problems are encountered, instructions are provided on actions to be taken. At a minimum, SOPs should address the following:

- Installation, setup, and checkout

- Site operations and calibrations

- Operational checks and preventive maintenance

- Data collection protocols

- Data validation steps

- Data archiving

8.5.2   Preventive Maintenance

8.5.2.1 Wind Speed

The anemometer has just one mechanical system which will benefit from preventive maintenance. That is the bearing assembly. There are two strategies from which to choose. One is to change the bearings (or the entire instrument if a spare is kept for that purpose) on a scheduled basis and the other is to make the change when torque measurements suggest change is in order. The former is most conservative with respect to data quality assuming that any time a torque measurement indicates a bearing problem, the bearing will be changed as a corrective maintenance action.

As routine calibrations become less frequent (8.3.5), the probability increases that a starting torque measurement will be made which indicates the anemometer is outside its performance specification. This will effect both the threshold (by increasing it) and the transfer function (by moving the non-linear threshold toward high speeds). It is unlikely that corrections can be properly made to the data in this case. The consequence might be the loss of a half-year's

data, if that is the period for routine calibration. If experience indicates that the anemometer bearing assembly shows serious wear at the end of one year or two years (based on torque measurements), a routine change of bearings at that frequency is recommended.

8.5.2.2 Wind Direction

The wind vane usually has two mechanical systems which will benefit from preventive maintenance. The bearing assembly is one and can be considered in the same way as the anemometer bearing assembly described above. The other is the potentiometer which will certainly "wear out" in time. The usual mode of failure for a potentiometer is to become noisy for certain directions and then inoperative. The noisy stage may not be apparent in the average direction data. If σ_A is calculated, the noise will bias the value toward a higher value. It will probably not be possible to see early appearance of noise in the σ_A data. When it becomes obvious that the σ_A is too high, some biased data may already have been validated and archived. Systems with time constant circuits built into the direction output will both mask the noise from the potentiometer (adding to the apparent potentiometer life) and bias the σ_A toward a lower value. Such circuits should not be used if they influence the actual output capability of the sensor. Each manufacturer may be different in their selection of a source and specifications used in buying potentiometers. The operator needs to get an expected life for the potentiometer from the manufacturer and monitor the real life with a noise sensitive test. An oscilloscope is best and can be used without disrupting the measurement. When potentiometer life expectations have been established, a preventive maintenance replacement on a conservative time basis is recommended.

8.5.2.3 Temperature and Temperature Difference

Aspirated radiation shields use fans which will also fail in time. The period of this failure should be several years. The temperature error resulting from this failure will be easily detected by a QC meteorologist inspecting the data. Some aspirated radiation shields include an air flow monitoring device or a current check which will immediately signal a disruption in aspiration. Preventive maintenance is not required but spare fans should be on the shelf so that a change can be made quickly when failure does occur.

8.5.2.4 Dew Point Temperature

Field calibration checks of the dew point temperature measurement system can be made with a high-quality Assmann-type or portable, motor-aspirated psychrometer. Sling psychrometers should not be used. Several readings should be taken at the intake of the aspirator or shield at night or under cloudy conditions during the day. These field checks should be made at least monthly, or in accordance with manufacturer's suggestions, and should cover a range of relative humidity values.

Periodically (at least quarterly) the lithium chloride in dew cells should be removed and recharged with a fresh solution. The sensor should be field-checked as described above before and at least an hour after the lithium chloride solution replacement.

If cooled-mirror type dew point systems are used, follow the manufacturer's service suggestions initially. The quality of the data from this method of measurement is dependent upon the mirror being kept clean. The frequency of service required to keep the mirror clean is a function of the environment in which the sensor is installed. That environment may vary with seasons or external weather conditions. If changes in dew point temperature of a magnitude larger than can be tolerated are found after service scheduled according to the manufacturer's suggestion, increase the service frequency until the cleaning becomes preventive maintenance rather than corrective service. This period will vary and can be defined only by experience. Station log data must include the "as found" and the "as left" measurements. Dew point temperature does not change rapidly (in the absence of local sources of water) and the difference between the two measurements will usually be the instrument error due to a dirty mirror.

8.5.2.5 Precipitation

The gauge should be inspected at regular intervals using a bubble level to see that the instrument base is mounted level. Also, the bubble level should be placed across the funnel orifice to see that it is level. The wind screen should also be checked to see that it is level, and that it is located l/2 inch above the level of the orifice, with the orifice centered within the screen.

8.5.2.6 Pressure

The output of the pressure sensor should be regularly checked against a collocated instrument. A precision aneroid barometer can be used for this check. The collocated barometer should be occasionally checked against a mercurial barometer reading at a nearby NWS station.

8.5.2.7 Radiation

The optical hemispheres on pyranometers and net radiometers should be cleaned frequently (preferably daily) with a soft, lint-free cloth. The surfaces of the hemispheres should be regularly inspected for scratches or cracks. The detectors should be regularly inspected for any discoloration or deformation. The instruments should be inspected during cool temperatures for any condensation which may form on the interior of the optical surfaces.

While calibrations must be done by the manufacturer, radiation can be field-checked using a recently-calibrated, collocated instrument. Since signal processing is particularly critical for these sensors, the collocated instrument should also use its own signal conditioner and data recording system for the check. This kind of field check should be done every six months.

It is mandatory to log "as found" and "as left" information about the parts of the system which seem to require work. Without this information it becomes difficult, if not impossible, to assess what data are usable and what are not.

8.6   Data Validation and Reporting

Data validation is a process in which suspect data are identified and flagged for additional review and corrective action as necessary. The data validation process provides an additional level of quality assurance for the monitoring program. Some problems that may escape detection during an audit (e.g., a wind vane that occasionally gets stuck) are often easily identified during data validation.

Data validation should be performed by a person with appropriate training in meteorology who has a basic understanding of local meteorological conditions and the operating principles of the instruments.

8.6.1   Preparatory Steps

Preparatory steps prior to data validation include: collection and storage of the raw data, backup, data reduction, transfer of data off-site, and preliminary review. These steps are discussed in the following:

- Collection and storage on-site (as appropriate) of the "raw" signals from the sensors, followed by real-time processing of the "raw" data by the data acquisition system to produce reduced, averaged values of the meteorological variables. The reduced data are stored on the data acquisition system's computer, usually in one or more ASCII files.

- Transfer of the reduced data to a central data processing facility at regular intervals (e.g., daily). Once the data are received at the central facility, they should be reviewed by an experienced data technician as soon as possible to verify the operational readiness of the monitoring site. Backup copies of the data should be prepared and maintained on-site and off-site.

Data collected by the monitoring systems can usually be obtained by polling the data system at a site from the central facility using a personal computer, modem, and standard telecommunications software. Other options that are available for communications with a remote site include leased-line telephone service, local or wide area network (LAN, WAN) connections, Internet access, and satellite telemetry. For immediate turnaround of data, the operator can transfer the data to the central facility using a personal computer equipped with a modem and communications software.

8.6.2 Levels of Validation

A level of validation, for the purposes of this guidance, is a numeric code indicating the degree of confidence in the data. These levels provide some commonality among data collected and quality controlled by different agencies, and help ensure that all data have received a comparable level of validation. Various data validation "levels" that apply to air quality and meteorological data have been defined by Mueller and Watson **[66]** and Watson et al. **[67]**. Basically, four levels of data validation have been defined:

- **Level 0** data validation is essentially raw data obtained directly from the data acquisition systems in the field. Level 0 data have been reduced and possibly reformatted, but are unedited and unreviewed. These data have not received any adjustments for known biases or problems that may have been identified during preventive maintenance checks or audits. These data should be used to monitor the instrument operations on a frequent basis (e.g., daily), but should not be used for regulatory purposes until they receive at least Level 1 validation.

- **Level 1** data validation involves quantitative and qualitative reviews for accuracy, completeness, and internal consistency. Quantitative checks are performed by software screening programs (**see Section 8.7.3.2**) and qualitative checks are performed by meteorologists or trained personnel who manually review the data for outliers and problems. Quality control flags, consisting of numbers or letters, are assigned to each datum to indicate its quality. A list of suggested quality control codes is given in Table 8-3. Data are only considered at Level 1 after final audit reports have been issued and any adjustments, changes, or modifications to the data have been made.

- **Level 2** data validation involves comparisons with other independent data sets. This includes, for example, intercomparing collocated measurements or making comparisons with other upper-air measurement systems.

- **Level 3** validation involves a more detailed analysis when inconsistencies in analysis and modeling results are found to be caused by measurement errors.

8.6.3 Validation Procedures

All necessary supporting material, such as audit reports and any site logs, should be readily available for the level 1 validation. Access to a daily weather archive should be provided for use in relating suspect data with to local and regional meteorological conditions. Any problem data, such as data flagged in an audit, should be corrected prior to the level 1 data validation. The validation procedures described in the following include screening, manual review, and comparison.

Table 8-3

Suggested quality control (QC) codes for meteorological data.

Code	Meaning	Description
0	Valid	Observations that were judged accurate within the performance limits of the instrument.
1	Estimated	Observations that required additional processing because the original values were suspect, invalid, or missing. Estimated data may be computed from patterns or trends in the data (e.g., via interpolation), or they may be based on the meteorological judgment of the reviewer.
2	Calibration applied	Observations that were corrected using a known, measured quantity (e.g., instrument offsets measured during audits).
3	Unassigned	Reserved for future use.
4	Unassigned	Reserved for future use.
5	Unassigned	Reserved for future use.
6	Failed automatic QC check	Observations that were flagged with this QC code did not pass screening criteria set in automatic QC software.
7	Suspect	Observations that, in the judgment of the reviewer, were in error because their values violated reasonable physical criteria or did not exhibit reasonable consistency, but a specific cause of the problem was not identified (e.g., excessive wind shear in an adiabatic boundary layer). Additional review using other, independent data sets (Level 2 validation) should be performed to determine the final validity of suspect observations.
8	Invalid	Observations that were judged inaccurate or in error, and the cause of the inaccuracy or error was known (e.g., winds contaminated by ground clutter or a temperature lapse rate that exceeded the autoconvective lapse rate). Besides the QC flag signifying invalid data, the data values themselves should be assigned invalid indicators.
9	Missing	Observations that were not collected.

8.6.3.1 Data Screening

Screening procedures generally include comparisons of measured values to upper and lower limits; these may be physical limits, such as an instrument threshold, or may be established based on experience or historical data. Other types of procedures employed in screening include assessments based on the rate of change of a variable (in these data that change too rapidly or not at all are flagged as suspect) and assessments based on known physical principles relating two or more variables (e.g., the dew point should never exceed the dry-bulb temperature).

Screening may be regarded as an iterative process in which range checks and other screening criteria are revised as necessary based on experience. For example, an initial QA pass of a data set using default criteria may flag values which upon further investigation are determined to be valid for the particular site. In such cases, one or more follow-up QA passes using revised criteria may be necessary to clearly segregate valid and invalid data. Suggested screening criteria are listed in Table 8-4.   Data which fail the screening test should be flagged for further investigation.

8.6.3.2 Manual Review

The manual review should result in a decision to accept or reject data flagged by the screening process. In addition, manual review may help to identify outliers that were missed by screening. This review should be performed by someone with the necessary training in meteorological monitoring.

In the typical manual review, data should be scanned to determine if the reported values are reasonable and in the proper format. Periods of missing data should be noted and investigated. Data should also be evaluated for temporal consistency. This is particularly useful for identifying outliers in hourly data. Outliers should be reviewed with reference to local meteorological conditions. Data are considered to be at Level 1 validation following the manual review and can be used for modeling and analysis.

8.6.3.3 Comparison Program

After the data have passed through the screening program, they should be evaluated in a comparison program. Randomly selected values should be manually compared with other available, reliable data (such as, data obtained from the nearest National Weather Service observing station). At least one hour out of every 10 days should be randomly selected. To account for hour-to-hour variability and the spatial displacement of the NWS station, a block of several hours may be more desirable. All data selected should be checked against corresponding measurements at the nearby station(s). In addition, monthly average values should be compared with climatological normals, as determined by the National Weather Service from records over a 30-year period. If discrepancies are found which can not be explained by the geographic difference in the measurement locations or by regional climatic variations, the data should be flagged as questionable.

Table 8-4

Suggested Data Screening Criteria

Variable	Screening Criteria: Flag data if the value
Wind Speed	- is less than zero or greater than 25 m/s
	- does not vary by more than 0.1 m/s for 3 consecutive hours
	- does not vary by more than 0.5 m/s for 12 consecutive hours
Wind Direction	- is less than zero or greater than 360 degrees
	- does not vary by more than 1 degree for more than 3 consecutive hours
	- does not vary by more than 10 degrees for 18 consecutive hours
Temperature	- is greater than the local record high
	- is less than the local record low
	(The above limits could be applied on a monthly basis.)
	- is greater than a 5°C change from the previous hour
	- does not vary by more than 0.5°C for 12 consecutive hours
Temperature Difference	- is greater than 0.1°C/m during the daytime
	- is less than -0.1°C/m during the night time
	- is greater than 5.0°C or less than -3.0°C
Dew Point Temperature	- is greater than the ambient temperature for the given time period
	- is greater than a 5°C change from the previous hour
	- does not vary by more than 0.5°C for 12 consecutive hours
	- equals the ambient temperature for 12 consecutive hours
Precipitation	- is greater than 25 mm in one hour
	- is greater than 100 mm in 24 hours
	- is less than 50 mm in three months
	(The above values can be adjusted based on local climate.)
Pressure	- is greater than 1060 mb (sea level)
	- is less than 940 mb (sea level)
	(The above values should be adjusted for elevations other than sea level.)
	- changes by more than 6 mb in three hours
Radiation	- is greater than zero at night
	- is greater than the maximum possible for the date and latitude

8.6.3.4 Further Evaluations

Any data which are flagged by the screening program or the comparison program should be evaluated by personnel with meteorological expertise. Decisions must be made to either accept the flagged data, or discard and replace it with back-up or interpolated data, or data from a nearby representative monitoring station (see Section 1). Any changes in the data due to the validation process should be documented as to the reasons for the change. If problems in the monitoring system are identified, corrective actions should also be documented. Any edited data should continue to be flagged so that its reliability can be considered in the interpretation of the results of any modeling analysis which employs the data.

8.6.4   Schedule and Reporting

Data should be retrieved on a daily basis and reviewed for reasonableness to ensure that the instrument is operating properly. Level 1 data validation should be performed as frequently as possible (e.g., bi-weekly or monthly). At a minimum, validation should be done weekly for the first month after the instrument is installed, so that any potential problems can be identified and quickly resolved to avoid significant data losses.

It is important to maintain detailed, accurate records of changes to the data and the data quality control codes. These records will save time and effort if questions arise about specific data at a later date. Reports should include the following information:

- Who performed the quality control validation, type of data validated, and when the validation was completed.

- Any adjustments, deletions, or modifications, with a justification or reason for the change.

- Identification of data points that were flagged as suspect or invalid, and the reason why they were flagged.

- Systematic problems that affected the data.

8.7   Recommendations

Quality Assurance/Quality Control (QAQC) procedures should be documented in a Quality Assurance Project Plan (QAPP) and approved by the appropriate project or organizational authority. These procedures should provide quantitative documentation to support claims of accuracy and should be conducted by persons independent of the organization responsible for the collection of the data and the maintenance of the measurement systems.

Procurement documents for meteorological monitoring systems should include the specifications for instrument systems and should identify the test method by which conformance with the specification will be determined. Persons responsible installing meteorological systems should review documentation provided on conformance-testing and should conduct independent

acceptance tests to verify claims of accuracy. All acceptance-testing activities should be documented in the station log.

Routine system calibrations and system audits should be performed at the initiation of a monitoring program (within 30 days of start-up) and at least every six months thereafter. More frequent calibrations and audits may be needed in the early stages of the program if problems are encountered, or if valid data retrieval rates are unacceptably low. Documentation of all calibrations should include a description of the system "as found", details of any adjustments to the instrument, and a description of the system "as left"; this documentation is necessary for any claims of data validity.

Regular and frequent routine operational checks of the monitoring system are essential to ensuring high data retrieval rates. These should include visual inspections of the instruments for signs of damage or wear, inspections of recording devices to ensure correct operation and periodic preventive maintenance. The latter should include periodic checks of wind speed and wind direction bearing assemblies, cleaning of aspirated shield screens in temperature systems, removal and recharging (at least quarterly) of lithium chloride dew cells, cleaning of the mirror in cooled mirror dew cells, clearing the precipitation gauge funnel of obstructing debris, and frequent (preferably daily) cleaning of the optical surface of a pyranometer or net radiometer. Also crucial to achieving acceptable valid data retrieval rates is the regular review of the data by an experienced meteorologist. This review should include visual scanning of the data, and automated screening and comparison checks to flag suspect data. This review should be performed weekly, and preferably on a daily basis.

9. UPPER-AIR MONITORING

This section provides guidance for the most widely used technologies employed for monitoring upper-air meteorological conditions; these include radiosondes and ground-based remote sensing platforms: sodar (Sound Detection and Ranging), radar (Radio Detection and Ranging), and RASS (Radio Acoustic Sounding System). While they are not covered in detail, other (emerging) technologies such as lidar (Light Detection and Ranging) may provide alternative means for the collection of upper-air meteorological data.

The material is organized such that information necessary to the understanding of the technology (Sections 9.1 through 9.3) precedes the guidance (Sections 9.4 through 9.7). The sections are as follows: Section 9.1 provides information necessary to the understanding of balloon-based sounding instruments and ground-based remote sensing technologies. Section 9.2 provides information on the performance characteristics of these systems; Section 9.3 discusses monitoring objectives and goals for monitoring of the boundary layer in support of air quality dispersion modeling; Section 9.4 provides guidance on siting and exposure of upper-air monitoring systems; Section 9.5 provides guidance on installation and acceptance testing; Section 9.6 provides guidance on quality assurance; and Section 9.7 provides guidance for data processing and management.

9.1   Fundamentals

Table 9-1 provides an overview of the upper-air monitoring systems included in this guidance. Necessary details describing the operation of each of the monitoring platforms [Radiosonde (9.1.2), Doppler Sodar (9.1.3), Radar Wind Profiler (9.1.4), and RASS (9.1.5)] is preceded by a description of the various meteorological variables that are measured by, or derived from measurements obtained with these platforms

9.1.1   Upper-Air Meteorological Variables

Meteorological variables measured/reported in upper-air monitoring programs include wind direction, wind speed, pressure, temperature, and humidity. With some exceptions (e.g., radiosonde measurements of pressure, temperature, and humidity), the upper-air data for these variables are based on indirect measurements; i.e., the desired variable is derived from measurements of other variables which are measured directly. This is a significant difference from the in situ measurements of these variables; i.e., when monitored in situ (such as from a meteorological tower) these variables are measured directly. This difference has significant implications for calibrations and audits of upper-air measurement systems (see Section 9.6).

Fundamentals related to upper-air monitoring of wind, pressure, temperature, and humidity are presented in the following. This is followed by information on estimating mixing heights and stability for use in dispersion modeling. Although the latter are often included in discussions of upper-air meteorological conditions, they are not really upper-air variables; a more

accurate classification of mixing height would describe it as a boundary layer variable which can be derived from upper-air measurements. Stability, as defined for use in dispersion modeling, is a surface layer variable and is not necessarily related to or correlated with upper-air measurements.

Wind Upper-air wind speeds and wind directions are vector-averaged measurements. None of the measurement systems described in the following sections provide a means to measure winds as scaler quantities, as is done with cup and vane sensors mounted on an instrumented tower. While tower-based measurements near the surface are easily obtained, there are very few instrumented tall towers that can provide vertical profiles of upper-air winds over the altitudes needed for some air quality applications.

Upper-air wind data comprise either path averages (radiosondes) or volume averages (remote sensors) rather than point measurements. For air quality programs, where the interest is mainly to characterize winds in the atmospheric boundary layer (ABL) and lower troposphere, radiosonde data are typically averaged over vertical layers with a depth of approximately 45 to 75 meters (m). Wind data provided by sodars are typically averaged over layers that are 5 to 100 m deep, while radar wind profiler data are usually averaged over 60 to 100 meter intervals. The altitude at which the winds are reported is assumed to be the mid-point of the layer over which the winds are averaged. Averaging periods for upper-air wind data also vary depending on the instrument system used. An individual wind data report from a radiosonde sounding system is typically averaged over no more than 30 to 120 seconds, representing averages of 60 to 700 meters. The averaging interval for winds measured by sodars and radar profilers is usually on the order of 15 to 60 minutes.

Upper-air wind data are needed to accurately characterize upper-air transport. For example, observing and resolving the vertical shear of the horizontal wind (both speed and directional changes with height) can be important for air quality model applications. Figure 9-1 shows a plot of upper-air winds measured by a radiosonde sounding system, along with simultaneous profiles of temperature, dew-point temperature, and potential temperature. The wind data are represented in the "wind barb" format, in which the direction of the wind is indicated by the orientation of an arrow's shaft (relative to true north, which is toward the top of the figure), and the wind speed is indicated by the number and length of barbs attached to the shaft. Note the change in wind speed and direction that is evident in the first few hundred meters of the sounding. In this case, below about 280 meters the winds are east-southeasterly. Above this level the winds veer (turn clockwise) with height to become southerly, southwesterly, then westerly. This is a simple example of a pattern that is common in upper-air measurements; in fact, much more complex wind shear conditions are often observed. Wind shear conditions can have important implications with respect to air quality, because of the different transport and turbulence conditions that can exist at different altitudes where air pollutants may be present.

Shear patterns such as those depicted in Figure 9-1 occur in part because of the frictional drag exerted on the atmosphere by the earth's surface. The atmospheric boundary layer is generally defined as the layer of the atmosphere within which the dynamic properties (i.e., winds) and thermodynamic properties (i.e., temperature, pressure, moisture) are directly influenced by the earth's surface. Factors that influence the vertical distribution of winds include horizontal

gradients in temperature (thermal wind effects), the development of local temperature and pressure gradients in shoreline settings (land/sea-breeze circulations) and complex terrain environments (mountain-valley airflows), vertical momentum transport by turbulent eddies, and diurnal reductions in frictional stress at night that can lead to the formation of low-level jets. Processes such as these are described in references **[68]** and **[69]**; examples of the effects of such circulations on air quality are described in reference **[70]**.
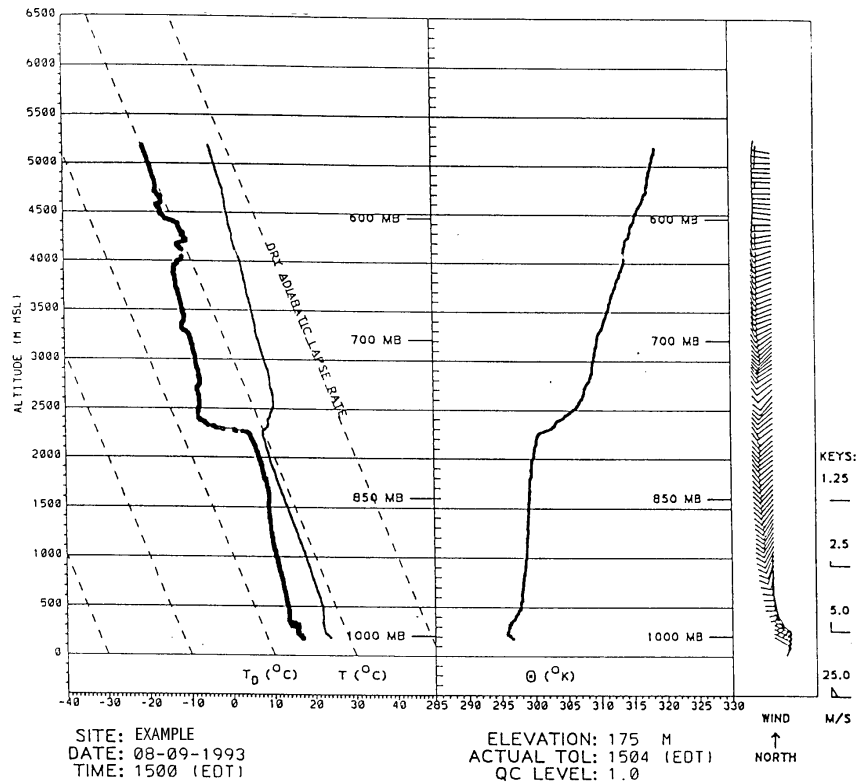
Figure 9-1 Example wind and temperature profiles from a radiosonde sounding system.

Consequently, upper-air wind data are critical to air quality analysis and modeling efforts. The data are used for the assessment of transport characteristics, as direct input to Gaussian dispersion models, and in the initialization and application of meteorological models (that are used to prepare time-varying, three-dimensional meteorological fields for puff and grid-based air quality models).

Upper-air wind speeds are almost always reported in units of meters per second (ms^{-1}) or knots (nautical miles per hour). Wind direction is reported as the direction from which the wind is blowing in degrees (clockwise) relative to true north. Altitude is usually reported in meters or feet and must be defined as corresponding to height above mean sea level or height above ground

level. Radiosonde data are typically reported as height above mean sea level (msl), whereas wind data collected by the remote sensing systems are often reported as height above ground level (agl).

Some remote sensing systems described in these guidelines provide a measure of vertical velocity. To date, however, little use has been made of these data in air quality modeling or data analysis applications. Additional work is needed (possibly on a case-by-case basis) to determine the utility of these data for air quality applications.

Pressure Vertical profiles of atmospheric pressure are measured during radiosonde ascents. The remote sensing systems considered in this document do not measure pressure. Pressure data are critical for radiosonde soundings because they are used to calculate the altitude of the sonde (strictly speaking, the geopotential altitude). Differential global position systems (GPS) rawinsonde systems are being developed that will be able to measure the altitude of the sonde directly, but pressure data will still be needed to support many modeling and data analysis efforts. For air quality purposes, pressure data are used in the application of meteorological models, and as direct input to air quality models. Pressure is reported in units of millibars (mb) or hectopascals (hPa).

Temperature Upper-air temperature measurements are most commonly obtained using radiosonde sounding systems. Radiosonde temperature measurements are point measurements. These can be obtained every few seconds, yielding a vertical resolution of a few meters to about 10 m, depending on the rate of ascent of the balloon.

Temperature data can also be obtained using RASS. RASS temperature measurements are volume averages, with a vertical resolution comparable to that of the wind measurements reported by the remote sensing systems (i.e., 50 to 100 m). RASS measures the virtual temperature (T_v) of the air rather than the dry-bulb temperature (T). The virtual temperature of an air parcel is the temperature that dry air would have if its pressure and density were equal to those of a parcel of moist air, and thus T_v is always higher than the dry-bulb temperature. Under hot and humid conditions, the difference between T_v and T is usually on the order of a few (2 to 3) degrees C; at low humidity, differences between T_v and T are small. Given representative moisture and pressure profiles, temperature can be estimated from the virtual temperature measurements.

Temperature data are used widely in air quality analysis and modeling, including the application and evaluation of meteorological models, and as direct input to air quality models. The vertical temperature structure (stability) influences plume rise and expansion and thus the vertical exchange of pollutants. Temperature also affects photolysis and chemical reaction rates. Temperature is reported in degrees Celsius (°C) or Kelvins (K).

Moisture Like pressure, upper-air moisture measurements suitable for air quality applications are primarily obtained using radiosonde sounding systems. The sampling frequency and vertical and temporal resolution of the moisture data are the same as the other thermodynamic variables measured by these systems. Moisture is most commonly measured directly as relative humidity (RH), and is reported as percent RH or as dew-point temperature (T_d) in °C (or frost point temperature). Dew-point depression, the difference between

temperature and dew-point temperature (T - T_d), is also a commonly reported variable. Some radiosonde sounding systems measure the wet-bulb temperature instead, and determine RH and dew-point temperature through the psychrometric relationship.

Upper-air moisture profiles are used in the initialization and application of meteorological models, and as direct input to air quality models. Moisture data can be important to a successful meteorological modeling effort, because the accurate simulation of convective development (clouds, precipitation, etc.) depends on an accurate representation of the three-dimensional moisture field. Upper-air moisture data are also useful to the understanding of the formation and growth of aerosols, which grow rapidly at high relative humidity (90 to 100 percent).

Mixing Height For the purposes of this guidance, mixing height is defined as the height of the layer adjacent to the ground over which an emitted or entrained inert non-buoyant tracer will be mixed (by turbulence) within a time scale of about one hour or less (adapted from Beyrich [43] . This concept of a mixing height was first developed for characterizing dispersion in a daytime convective boundary layer (CBL). Since tracer measurements are impractical for routine application, alternative methods are recommended for estimating mixing heights based on more readily available data (Table 9-2). The Holzworth method [44] is recommended for use when representative NWS upper-air data are available. This procedure relies on the general theoretical principle that the lapse rate is roughly dry adiabatic (no change in potential temperature with height) in a well-mixed daytime convective boundary layer (CBL); the Holzworth method is described in Section 6.5.1. Other alternatives include using estimates of mixing heights provided in CBL model output (references [45] and [46]). Mixing heights derived from remote sensing measurements of turbulence or turbulence related parameters are discussed in the following.

Turbulence, or turbulence related measurements (e.g, backscatter measurements from a sodar or refractive index measurements from a radar wind profiler) though not surrogates for an inert tracer can sometimes be used to estimate mixing heights since, under certain conditions, such measurements correlate with the top of the mixed layer. In looking at these measurements, one attempts to determine depth of the layer adjacent to the surface within which there is continuous or intermittent turbulence; this is a non-trivial exercise since turbulence varies considerably, not only with height, but with time and location. This variability is dependent upon which processes control/dominate the production of turbulence near the surface; these processes are discussed in the following.

The production of turbulent eddies during the daytime is dominated (under clear sky conditions) by heating of the ground surface and (under overcast conditions) by frictional drag. Daytime vertical mixing processes can be vigorous (especially under convective -conditions) and can produce a well mixed or nearly uniform vertical concentration profile of an inert tracer. During the nighttime, there are several processes that contribute to the production of turbulence including wind shear (created near the ground by friction), variations in the geostrophic wind, and the presence of a low-level jet (wind shear both below and above the jet can enhance turbulence). Nighttime vertical mixing processes are typically patchy and intermittent, and not capable of producing a well-mixed uniform vertical concentration profile.

Table 9-2

Methods for Determining Mixing Heights

Platform	Variable Measured	Advantages/limitations
Aircraft LIDAR	Inert tracer	Consistent with the definition of mixing height as used in dispersion modeling. Labor intensive, not practical for routine applications.
Rawinsonde	Potential temperature	A relatively robust technique for estimating the daytime (convective) mixing depth. Limited by the non-continuous nature of rawinsonde launches.
Sodar	Turbulence Acoustic backscatter	Used for continuous monitoring of boundary layer conditions. The range of a sodar, however, is limited; estimates of the mixing height are possible only when the top of the mixed layer is within the range of the sodar. A good tool for monitoring the nocturnal, surface-based temperature inversion - although different from the mixing height, the nocturnal inversion is equally important for modeling nocturnal dispersion conditions.
Radar wind profiler	Refractive index	Used for continuous monitoring of boundary layer conditions.
RASS	Virtual temperature	The virtual temperature profile obtained using a RASS is used to estimate the convective mixing height in the same manner that temperature data are used (limited to the range of the RASS $\approx$ 1 km..).

Wind turbulence parameters and/or acoustic backscatter profiles derived from sodar data can also be used to estimate mixing height. These data can be used for both daytime and nighttime conditions, but only when the top of the mixing height is within the range of the sodar.

The refractive index structure parameter (C_n^2) calculated from radar wind profiler reflectivity measurements can also be used to estimate mixing height **[71]**. During nighttime hours, however, the mixing height may be below the range of the radar wind profile.

The virtual temperature profile obtained using a RASS instrument can be used to estimate convective mixing height in the same manner that temperature data are used; this is possible only when the mixing height is within the range of the RASS.

Turbulence Some sodars report wind turbulence parameters. In using these parameters, one must remember that sodars measure the vector components of the wind. Furthermore, there may be significant differences in time and space between the sampling of the components so that any derived variables using more than one component may be affected by aliasing. Thus, the derived turbulence parameters from sodars are generally not the same parameters that models expect for input. Numerous studies have been performed comparing sodar-based turbulence

statistics with tower-based turbulence statistics. Findings from these studies have generally shown that measurements of the standard deviation of the vertical component of the wind speed (σ_w) are in reasonable agreement , while the standard deviation calculations incorporating more than one component (e.g., σ_θ) are not **[72]**. It is therefore recommended that, unless models are designed to use sodar-type statistical parameters, the use of derived turbulence parameters be limited to single component calculations such as σ_w. Note however that the utility of σ_w will depend upon the resolution of the sodar system.

9.1.2   Radiosonde Sounding System

Radiosonde sounding systems use *in situ* sensors carried aloft by a small, balloon-borne instrument package (the radiosonde, or simply "sonde") to measure vertical profiles of atmospheric pressure, temperature, and moisture (relative humidity or wet bulb temperature) as the balloon ascends. In the United States, helium is typically used to inflate weather balloons. Hydrogen is also used. The altitude of the balloon is typically determined using thermodynamic variables or through the use of satellite-based Global Positioning Systems (GPS). Pressure is usually measured by a capacitance aneroid barometer or similar sensor. Temperature is typically measured by a small rod or bead thermistor. Most commercial radiosonde sounding systems use a carbon hygristor or a capacitance sensor to measure relative humidity directly, although a wet-bulb sensor is also used by some systems. With a wet bulb, relative humidity and dewpoint are calculated from psychrometric relationships. Ventilation of the sensors occurs as the balloon rises. The temperature sensor is usually coated to minimize radiational heating effects. The humidity sensor is usually shielded in a ventilated duct inside the sonde's enclosure to minimize exposure to solar radiation.

A radiosonde includes electronic subsystems that sample each sensor at regular intervals (e.g., every 2 to 5 seconds), and transmit the data to a ground-based receiver and data acquisition system. Power for the radiosonde is provided by small dry-cell or wet-cell batteries. Most commercial radiosonde systems operate at 404 MHZ or 1680 MHZ. Once the data are received at the ground station, they are converted to engineering units based on calibrations supplied by the manufacturer. The data acquisition system reduces the data in near-real time, calculates the altitude of the balloon, and computes wind speed and direction aloft based on information obtained by the data systems on the position of the balloon as it is borne along by the wind. Commercial systems available today are relatively compact and easy to operate. The radiosondes are typically smaller than a shoebox and weigh only a few hundred grams. Thus, the previous need to use a parachute to slow the radiosonde's descent after the balloon has burst has greatly diminished, although the manufacturer should still be consulted on this matter. The data systems are either personal computer (PC)-based, or self-contained with standard PC-type computer interfaces for data communications (e.g., RS-232). Data are stored on conventional PC-type hard disks and/or diskettes.

Upper-air winds (horizontal wind speed and direction) are determined during radiosonde ascents by measuring the position of the radiosonde relative to the earth's surface as the balloon ascends. By measuring the position of the balloon with respect to time and altitude, wind vectors can be computed that represent the layer-averaged horizontal wind speed and wind direction for

successive layers. The position data have typically been obtained using radio direction finding techniques (RDF) or one of the radio navigation (NAVAID) networks. The use of satellite-based GPS is becoming more common.

RDF systems use a tracking device called a radio theodolite to measure the position of the balloon relative to the ground station. The radio theodolite, which resembles a small tracking radar system, measures the azimuth and elevation angles to the radiosonde relative to the ground station. The radio theodolite automatically follows the motion of the balloon by tracking the primary lobe of the radiosonde's transmitter, making adjustments to the tilt and pointing direction of the antenna as it follows the signal from the sonde. The azimuth, elevation, and altitude information is then used by the data system to compute the length and direction of a vector projected onto the earth's surface that represents the resultant motion of the balloon over some suitable averaging period, typically 30 to 120 seconds.

With NAVAID systems, the radiosonde's position is determined by triangulation relative to the locations of the fixed NAVAID transmitters. The radiosonde and ground station have electronic subsystems to measure the time delay in the transmissions from the NAVAID sites and to convert this information into the relative motion of the radiosonde, from which winds aloft are computed.

GPS is a satellite navigation system, which is funded and controlled by the U.S. Department of Defense. The system was designed for and is operated by the U.S. military. GPS provides specially coded satellite signals that can be processed in a GPS receiver, enabling the receiver to compute position, velocity and time. GPS wind-finding system sondes consist of a 10-channel GPS (Global Positioning System) receiver as well as a platform for temperature, RH and pressure sensors.

The basic steps in performing a sounding involve: preparing the radiosonde (deploying the sensors, connecting the batteries, etc.); activating the data acquisition system and manually or automatically entering the radiosonde calibration information; inflating the balloon and attaching the sonde; releasing the balloon and activating the tracking system; monitoring the data during the sounding; and performing post-sounding procedures as required (e.g., completing sounding documentation, preparing backups of the data, transferring the data to a central data processing facility, etc.). For air quality programs, the entire procedure requires approximately one hour, and one to two operators. Prior to the release of the radiosonde, an accurate measurement must be made of the surface pressure to provide a baseline value for computing altitude from the radiosonde data. This baseline value is used to compute any offsets that are needed for the sonde's pressure measurements. A good quality barometer that is regularly calibrated and audited should be used to make this measurement. Other baseline readings that should be taken include temperature and moisture (wet bulb or relative humidity), and surface winds, although these data are typically not used to offset the sonde measurements.

High quality tracking information is necessary for obtaining high quality wind data within the atmospheric boundary layer. For monitoring programs with a strong emphasis on characterizing low-level boundary layer winds, it is important that the radio theodolite operator get the theodolite to "lock on" to the radiosonde transmission right from the moment of launch. Otherwise, a few minutes of wind data may be lost while the system acquires the signal and

begins tracking the radiosonde automatically. Due to this type of delay, for example, typical National Weather Service (NWS) data collection procedures result in a smoothing of the winds within approximately the lowest 300 m. With NAVAID systems, it is important to ensure that position information is being acquired prior to release of the balloon. At some sites, high terrain or other obstacles may block the NAVAID radio signals, so that the balloon must be airborne for a few minutes before accurate position information is available. This, too, can cause a few minutes of wind data to be lost at the beginning of a sounding. Normally autonomous (single receiver) GPS position data are only accurate to about 100 meters due to the use of selective availability by the military to introduce an "uncertainty" into the signal. To compensate for this error, the meteorological sounding systems use the base (receiving) station as a differential GPS location which can increase GPS accuracy to better than 1 meter. The horizontal drift of the radiosonde from the release location may also result in the incomplete characterization of the vertical structure of small (spatial and or temporal) scale features.

Generally speaking, radiosonde soundings made for boundary layer air quality studies do not need to achieve the kind of high altitude coverage required for soundings made by the NWS, where data to the tropopause and to stratospheric levels are needed for weather forecasting. For most air quality studies, the vertical range for radiosonde data will not need to exceed 10,000 m msl (approximately 300 mb), and data coverage to 5000 m msl (approximately 500 mb) will be sufficient. In this case, a smaller weather balloon than that used by the NWS, e.g., a 100-gram balloon as opposed to a 300- to 600-gram balloon, is adequate. Balloon size is stated as weight rather than diameter because the weight relates directly to the amount of free lift needed to achieve the desired ascent rate during a sounding, which in turn influences how much helium must be used and, therefore, the cost per sounding.

In a compromise between adequate ventilation of the temperature and moisture sensors on the sonde and good vertical resolution in the boundary layer, ascent rates used for soundings made during air quality studies (2 to 3 ms^{-1}) are also typically less than that used by the NWS (5 to 6 ms^{-1}). As noted earlier, these ascent rates are consistent with an elapsed time of approximately one hour. Thus, the vertical resolution of the thermodynamic data is usually 5 to 10 m, depending on the interval at which the data acquisition system samples the signals from the radiosonde and the time response of the sensor. The vertical resolution of the wind data ranges from approximately 45 to 200 m, depending on the type of sounding system used. The data averaging interval for radiosondes is 1 to 2 minutes in the lower part of a sounding (e.g., lowest 3000 m) and approximately 3 to 4 minutes in the upper part of a sounding.

9.1.3 Doppler Sodar

Commercial sodars operated for the purpose of collecting upper-air wind measurements consist of antennas that transmit and receive acoustic signals. A mono-static system uses the same antenna for transmitting and receiving, while a bi-static system uses separate antennas. The difference between the two antenna systems determines whether atmospheric scattering by temperature fluctuations (in mono-static systems), or by both temperature and wind velocity fluctuations (in bi-static systems) is the basis of the measurement. The vast majority of sodars in use are of the mono-static variety due to their more compact antenna size, simpler operation, and

generally greater altitude coverage. Figure 9-2 shows the beam configurations of mono-static and bi-static systems.

Mono-static antenna systems can be divided into two categories: those using multiple axis, individual antennas and those using a single phased-array antenna. The multiple-axis systems generally use three individual antennas aimed in specific directions to steer the acoustic beam. One antenna is generally aimed vertically, and the other two are tilted slightly from the vertical at an orthogonal angle. Each of the individual antennas may use a single transducer focused into a parabolic dish, or an array of speaker drivers and horns (transducers) all transmitting in-phase to form a single beam. Both the tilt angle from the vertical and the azimuth angle of each antenna need to be measured when the system is set up. Phased-array antenna systems use a single array of speaker drivers and horns (transducers), and the beams are electronically steered by phasing the transducers appropriately. To set up a phased-array antenna, one needs to measure the pointing direction of the array and ensure that the antenna is either level or oriented as specified by the manufacturer.
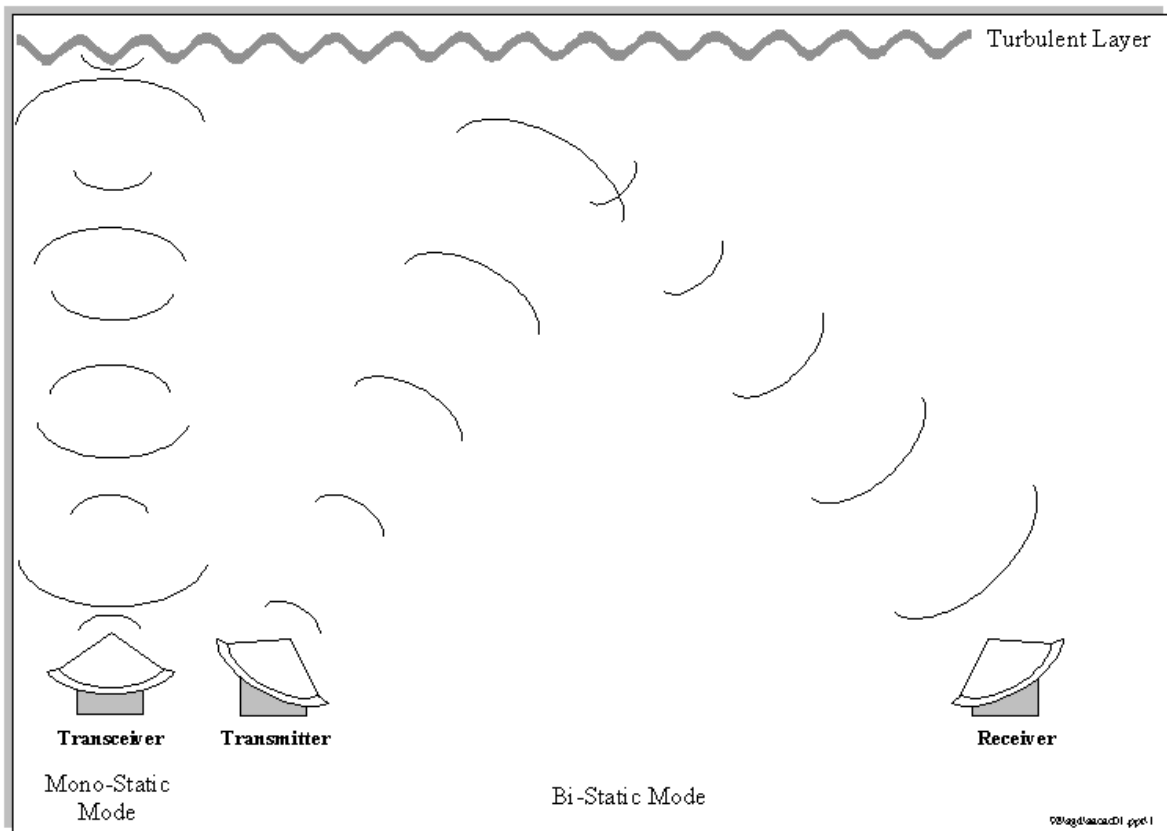

Figure 9-2 Simple depiction of a monostatic and bistatic sodar.

The horizontal components of the wind velocity are calculated from the radially measured Doppler shifts and the specified tilt angle from the vertical. The tilt angle, or zenith angle, is generally 15° to 30°, and the horizontal beams are typically oriented at right angles to one another. Since the Doppler shift of the radial components along the tilted beams includes the influence of both the horizontal and vertical components of the wind, a correction for the vertical velocity should be applied in systems with zenith angles less than 20°. In addition, if the system is located in a region where expected vertical velocities may be greater than about 0.2 ms^{-1}, corrections for the vertical velocity should be made regardless of the beam's zenith angle.

The vertical range of sodars is approximately 0.2 to 2 kilometers (km) and is a function of frequency, power output, atmospheric stability, turbulence, and, most importantly, the noise environment in which a sodar is operated. Operating frequencies range from less than 1000 Hz to over 4000 Hz, with power levels up to several hundred watts. Due to the attenuation characteristics of the atmosphere, high power, lower frequency sodars will generally produce greater height coverage. Some sodars can be operated in different modes to better match vertical resolution and range to the application. This is accomplished through a relaxation between pulse length and maximum altitude, as explained in Section 9.1.4 for radar wind profilers.

Sodar systems should include available options for maximizing the intended capabilities (e.g., altitude range, sampling resolution, averaging time) of the system and for processing and validating the data. The selection of installation site(s) should be made in consultation with the manufacturer and should consider issues associated with the operation of the sodar instrument. Training should be obtained from the manufacturer on the installation, operation, maintenance, and data validation. Additional information on these issues is provided in Section 9.5 of this document.

9.1.4   Radar Wind Profiler

Operating characteristics of three common types of radar wind profilers are given in Table 9-3. The categories included in the table are: 1) very high frequency (VHF) profilers that operate at frequencies near 50 MHZ; 2) ultra-high frequency (UHF) tropospheric profilers that operate at frequencies near 400 MHZ; and 3) UHF lower tropospheric profilers that operate at frequencies near 1000 MHZ. The guidance provided herein is intended for radar wind profilers that fall into the third category; i.e., UHF lower tropospheric profilers (also called boundary layer radar wind profilers).

Doppler radar wind profilers operate using principles similar to those used by Doppler sodars, except that electromagnetic (EM) signals are used rather than acoustic signals to remotely sense winds aloft. Figure 9-3 shows an example of the geometry of a UHF radar wind profiler equipped with a RASS unit (see Section 9.1.5). In this illustration, the radar can sample along each of five beams: one is aimed vertically to measure vertical velocity, and four are tilted off vertical and oriented orthogonal to one another to measure the horizontal components of the air's motion. A UHF profiler includes subsystems to control the radar's transmitter, receiver, signal processing, and RASS (if provided), as well as data telemetry and remote control.

Detailed information on profiler operation can be found in references **[73]** and **[74]**; a brief summary of the fundamentals is provided in the following. The radar transmits an electromagnetic pulse along each of the antenna's pointing directions. The duration of the transmission determines the length of the pulse emitted by the antenna, which in turn corresponds to the volume of air illuminated (in electrical terms) by the radar beam. Small amounts of the transmitted energy are scattered back (referred to as backscattering) toward and received by the radar. Delays of fixed intervals are built into the data processing system so that the radar receives scattered energy from discrete altitudes, referred to as range gates. The Doppler frequency shift of the backscattered energy is determined, and then used to calculate the velocity of the air toward or away from the radar along each beam as a function of altitude. The source of the backscattered energy (radar "targets") is small-scale turbulent fluctuations that induce irregularities in the radio refractive index of the atmosphere. The radar is most sensitive to scattering by turbulent eddies whose spatial scale is ½ the wavelength of the radar, or approximately 16 centimeters (cm) for a UHF profiler.
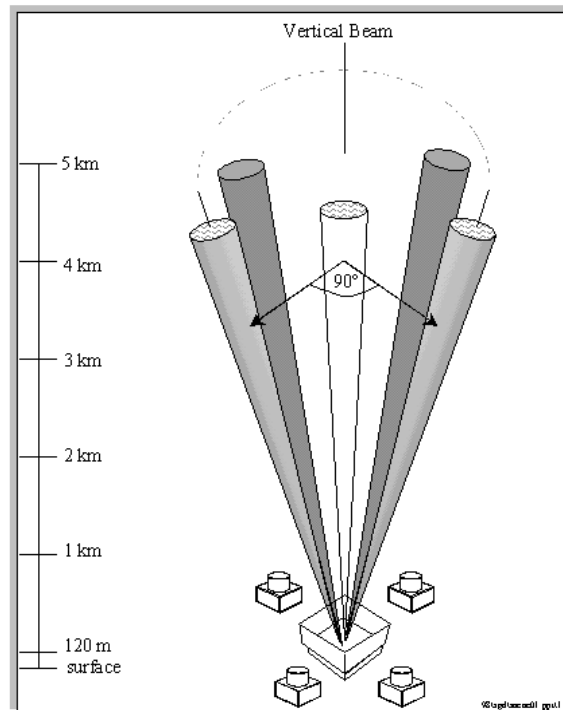
Figure 9-3 Schematic of sampling geometry for a radar wind profiler with RASS.

Table 9-3

Characteristics of radar wind profilers

Frequency Class	Antenna Size (m²)	Peak Power (kw)	Range (km)	Resolution (m)	Alias and Prototypes
50 MHZ	10,000	250	2-20	150-1000	Alias: VHF radar wind profiler Prototype: 50 MHZ (600 cm) profiler used in the Colorado Wind Profiler Network in 1983.
400 MHZ	120	40	0.2-14	250	Alias: UHF (tropospheric) radar wind profiler Prototypes: 404 MHZ (74 cm) profiler developed for the Wind Profiler Demonstration Network (WPDN) in 1988. 449 MHZ (67 cm) profiler operates at the approved frequency for UHF profilers and will eventually replace the 404 MHZ units. 482 MHZ (62 cm) profiler used by the German Weather Service.
1000 MHZ	3-6	0.5	0.1-5	60-100	Alias: UHF lower-tropospheric radar wind profiler Boundary layer radar wind profiler Lower-atmospheric radar wind profiler Prototypes: 915 MHZ (33 cm) profiler used in the Colorado Wind Profiler Network in 1983. 1290 MHZ (23 cm) boundary layer profiler used by the German Weather Service.

A profiler's (and sodar's) ability to measure winds is based on the assumption that the turbulent eddies that induce scattering are carried along by the mean wind. The energy scattered by these eddies and received by the profiler is orders of magnitude smaller than the energy transmitted. However, if sufficient samples can be obtained, then the amplitude of the energy scattered by these eddies can be clearly identified above the background noise level, then the mean wind speed and direction within the volume being sampled can be determined.

The radial components measured by the tilted beams are the vector sum of the horizontal motion of the air toward or away from the radar and any vertical motion present in the beam. Using appropriate trigonometry, the three-dimensional meteorological velocity components (u,v,w) and wind speed and wind direction are calculated from the radial velocities with corrections for vertical motions. A boundary-layer radar wind profiler can be configured to compute averaged wind profiles for periods ranging from a few minutes to an hour.

Boundary-layer radar wind profilers are often configured to sample in more than one mode. For example, in a "low mode," the pulse of energy transmitted by the profiler may be 60 m in length. The pulse length determines the depth of the column of air being sampled and thus the vertical resolution of the data. In a "high mode," the pulse length is increased, usually to 100 m or greater. The longer pulse length means that more energy is being transmitted for each sample, which improves the signal-to-noise ratio (SNR) of the data. Using a longer pulse length increases the depth of the sample volume and thus decreases the vertical resolution in the data. The greater energy output of the high mode increases the maximum altitude to which the radar wind profiler can sample, but at the expense of coarser vertical resolution and an increase in the altitude at which the first winds are measured. When radar wind profilers are operated in multiple modes, the data are often combined into a single overlapping data set to simplify post-processing and data validation procedures.

9.1.5   RASS

The principle of operation behind RASS is as follows: Bragg scattering occurs when acoustic energy (i.e., sound) is transmitted into the vertical beam of a radar such that the wavelength of the acoustic signal matches the half-wavelength of the radar. As the frequency of the acoustic signal is varied, strongly enhanced scattering of the radar signal occurs when the Bragg match takes place. When this occurs, the Doppler shift of the radar signal produced by the Bragg scattering can be determined, as well as the atmospheric vertical velocity. Thus, the speed of sound as a function of altitude can be measured, from which virtual temperature (T_v) profiles can be calculated with appropriate corrections for vertical air motion. The virtual temperature of an air parcel is the temperature that dry air would have if its pressure and density were equal to those of a sample of moist air. As a rule of thumb, an atmospheric vertical velocity of 1 ms^{-1} can alter a T_v observation by 1.6°C.

RASS can be added to a radar wind profiler or to a sodar system. In the former case, the necessary acoustic subsystems must be added to the radar wind profiler to generate the sound signals and to perform signal processing. When RASS is added to a radar profiler, three or four

vertically pointing acoustic sources (equivalent to high quality stereo loud speakers) are placed around the radar wind profiler's antenna, and electronic subsystems are added that include the acoustic power amplifier and the signal generating circuit boards. The acoustic sources are used only to transmit sound into the vertical beam of the radar, and are usually encased in noise suppression enclosures to minimize nuisance effects that may bother nearby neighbors or others in the vicinity of the instrument.

When RASS is added to a sodar, the necessary radar subsystems are added to transmit and receive the radar signals and to process the radar reflectivity information. Since the wind data are obtained by the sodar, the radar only needs to sample along the vertical axis. The sodar transducers are used to transmit the acoustic signals that produce the Bragg scattering of the radar signals, which allows the speed of sound to be measured by the radar.

The vertical resolution of RASS data is determined by the pulse length(s) used by the radar. RASS sampling is usually performed with a 60- to 100-m pulse length. Because of atmospheric attenuation of the acoustic signals at the RASS frequencies used by boundary layer radar wind profilers, the altitude range that can be sampled is usually 0.1 to 1.5 km, depending on atmospheric conditions (e.g., high wind velocities tend to limit RASS altitude coverage to a few hundred meters because the acoustic signals are blown out of the radar beam).

9.2   Performance Characteristics

The following references provide documentation of performance characteristics for the upper-air measurement platforms covered in this guidance (lidar is included for completeness):

- Rawinsonde **[9] [75] [76] [77] [78] [79] [80] [81]**

- Sodar   **[82] [83] [84] [85] [86] [87] [88]**

- Radar wind profiler   **[89] [90] [91] [92]**

- RASS   **[93] [94] [95] [96]**

- Lidar **[83] [97] [98] [99]**

9.2.1   Definition of Performance Specifications

Accuracy is defined as the degree of agreement of a measurement with an accepted reference or true value **[2]**. Determining the absolute accuracy of an upper-air instrument through an inter-comparison study is difficult because there is no "reference" instrument that can provide a known or true value of the atmospheric conditions. This is due in part to system uncertainties and inherent uncertainties caused by meteorological variability, spatial and temporal separation of the measurements, external and internal interference, and random noise. The only absolute accuracy check that can be performed is on the system electronics, by processing a simulated signal. Similarly, a true precision, or the standard deviation of a series of measured values about a mean measured reference value, can only be calculated using the system responses to repeated inputs of the same simulated signal.

The performance specifications provided by manufacturers for accuracy, precision, and other data quality objectives are derived in a number of ways, and it is prudent to understand the basis behind the published specifications. Manufacturers' specifications may be derived from the results of inter-comparison studies, from what the instrument system can resolve through the system electronics and processing algorithms, or a combination of these methods. It may not be practical for a user to verify the exact specifications claimed by the manufacturers. What is needed, however, is a means of verifying that the data obtained from an upper-air system compare reasonably to observations obtained from another measurement system. Guidance for system acceptance testing, field testing, auditing, and data comparison is provided in Section 9.6.

To quantify the reasonableness of the data, one compares observations from the upper-air system being evaluated to data provided by another sensor that is known to be operating properly. In assessing how well the sensors compare, two measures are commonly used. The first involves calculating the "systematic difference" between the observed variables measured by the two methods. The second involves calculating a measure of the uncertainty between the measurements, which is referred to as the "operational comparability" (or simply "comparability"), as described in reference **[100]**. Comparability, for these purposes, is the root-mean-square (rms) of a series of differences between two instruments measuring nearly the same population. The comparability statistic provides a combined measure of both precision and bias, and will express how well the two systems agree.

Using the ASTM notation **[100]**, the systematic difference (or bias) is defined as:

$$d = \frac{1}{n} \sum (x_{a,i} - x_{b,i}) \tag{9-1}$$

where

$$n \quad = \quad \text{number of observations}$$

$$x_{a,i} \quad = \quad i\text{th observation of the sensor being evaluated}$$

$$x_{b,i} \quad = \quad i\text{th observation of the "reference" instrument}$$

Operational comparability (or root-mean-square error) is defined as

$$c = \sqrt{\frac{1}{n} \sum (x_{a,i} - x_{b,i})^2} \tag{9-2}$$

Many of the inter-comparison programs discussed in the next section have evaluated instrument performance using the systematic difference and comparability statistics described

here. Other statistical measures that can be used include, for example, correlation coefficients and linear regression.

Another important performance specification for upper-air instrument systems is data recovery rate. Data recovery is usually calculated as the ratio of the number of observations actually reported at a sampling height to the total number of observations that could have been reported so long as the instrument was operating (i.e., downtime is usually not included in data recovery statistics but is treated separately). Data recovery is usually expressed as percent as a function of altitude. Altitude coverage for upper-air data is often characterized in terms of the height up to which data are reported 80 percent of the time, 50 percent of the time, etc.

9.2.2   Performance Characteristics of Radiosonde Sounding Systems

Radiosonde sounding systems are the most widely used upper-air instruments. The wind and thermodynamic data provided by these systems are critical to the numerical weather prediction (NWP) and forecasting programs conducted by all countries that provide such services. Thus, the performance characteristics of radiosondes and the relative accuracy of radiosonde winds have been the subject of a great deal of scrutiny over the last few decades. The World Meteorological Organization (WMO) and national weather agencies such as the U.S. NWS and British Meteorological Office have all sanctioned a number of inter-comparison studies to determine the performance characteristics of radiosonde systems (references **[9]**, **[75]**, and **[77]**). Inter-comparison and performance evaluation studies have also been conducted by independent researchers who have been interested in determining the accuracy of radiosonde wind and/or thermodynamic measurements for meeting specific research objectives (see reference**[81]** for a recent summary of some of these studies, especially those related to boundary-layer measurements). Some references are also provided in Table 9-4. Radiosonde systems will continue to be an important source of upper-air data for the foreseeable future, and efforts to characterize and improve radiosonde sounding system performance specifications continues **[79]**.

Performance tests of radiosonde systems have involved "flying" multiple radiosondes on the same balloon, and/or obtaining independent tracking information using high-precision tracking radars **[79]**. Such tests do not provide information on absolute accuracy of either the radiosondes or the tracking systems. Rather, they provide measures of the relative differences between comparable instrument systems, e.g., of temperature or relative humidity measured by different radiosondes flown at the same time and winds measured by radio theodolites or NAVAID systems. The NWS and WMO perform such tests to quantify the functional precision of the instruments, which is defined as the rms of the differences between the measurements, that is, if the differences have a Gaussian distribution then 67 percent of the differences would lie within the range specified by the functional precision. The functional precision is thus similar to the comparability statistic defined by Equation 9-2. Performance specifications for radiosonde systems are summarized in Table 9-1, the performance specifications are based on manufacturer's specifications and inter-comparison tests described in references **[77]** and **[79]**.

Errors and uncertainties encountered in radiosonde measurements, particularly errors in temperature and moisture, can occur at higher altitudes (e.g., beginning in the upper-troposphere), and are caused by factors such as exposure to solar radiation, sensor heating, and time lag. Data collected at lower altitudes (e.g., below about 10 km) do not tend to display such errors. Likewise, the relative accuracy of upper-air winds measured by radiosondes tends to decrease with increasing altitude. This is due in part to many weather services using radio theodolite sounding systems, where errors in tracking angles (especially elevation) become more troublesome as the balloon approaches the horizon and the antenna reaches its tracking limit.

At altitudes below about 10 km, radiosonde winds tend to show good agreement with other independent upper-air measurements **[79]**. As noted earlier in this document, there are circumstances under which data resolution within the lowest few hundred meters can be compromised.

9.2.3   Performance Characteristics of Remote Sensing Systems

Many of the studies that have been performed to estimate the accuracy and precision of remote sensors were based on inter-comparisons to tower-based measurements. These comparisons have generally assumed that the tower measurements provide the known standard and are representative of the same environment measured by the remote sensors. However, differences between point measurements from *in situ* sensors located on the tower and volume-averaged measurements from the remote sensors located near the tower are expected to lead to differences in the results, even though conditions for these inter-comparisons are likely as close to "ideal" as one could expect. The performance of remote profiling instrumentation is greatly influenced by individual site characteristics, instrument condition, and operating parameters established for the equipment.

Table 9-1 includes estimates of expected performance characteristics for remote sensing systems that are installed and working properly. These results should be used for establishing data quality objectives for upper-air programs and as a basis for interpreting results from inter-comparison programs or performance audits of upper-air equipment (see Section 9.6). To avoid ambiguities in wind direction associated with light and variable winds, it is recommended that the wind direction comparability calculations be made only when actual wind speeds are greater than approximately 2 ms^{-1}.

9.3   Monitoring Objectives and Goals

When the primary use of upper-air data is for the analysis and modeling of meteorological and air quality conditions in the boundary layer and lower troposphere, the focus of the upper air program should be to maximize the temporal and spatial resolution of the data collected in this portion of the atmosphere, i.e. the first one to three km. Each modeling and analysis application will have its own unique objectives and scales of interest. However there are certain characteristics that have a large bearing on the type of upper-air measurement system chosen, the manner in which it is operated, and data processing and archival procedures. These

characteristics include the duration of the measurement program, that is whether the measurements are part of a long-term monitoring program of seasonal to yearly extent, or a shorter-term intensive field campaign characterized by a greater number of measurements. The types of measured and derived meteorological variables required for the modeling/analysis, including the required spatial and temporal resolution, will also affect the choice of measurement system, as will the need, in many cases, to make comparable measurements with surface-based meteorological systems.

The choice of upper-air measurement technologies is considerably greater now than at any time in the last two decades. With that choice comes the need to carefully consider the requirements of the application and to choose and configure the appropriate systems. Considerable field experience has been gained in the use of the various measurement technologies, especially since 1990. The following discussion for each class of upper-air measurement system is meant to stimulate thinking regarding the best match of the system to the specific application.

9.3.1   Data Quality Objectives

Inherent in any measurement program is the need to establish data quality objectives. These relate the quality of measurements obtained to the level of uncertainty that decision makers are willing to accept in the data and results derived from the data [65]. Data quality objectives state how "good" the data need to be to satisfy the program objectives. The stated objectives generally include completeness, systematic difference, and comparability. Operators of the instruments should let the data quality objectives be determined based on instrument performance specifications and modeling and analysis needs. Data quality objectives should be specified for all of the primary variables measured by the instrument.

To check whether or not the data meet the data quality objectives from an instrument performance perspective, a comparison to another sensor that is known to be operating properly is recommended (see Section 9.5). In assessing how well the sensors compare, the systematic difference and the operational comparability can be computed and compared to the data quality objectives that are presented in Table 9-4.

In evaluating the sodar and radar wind profiler data, the primary criteria for comparison are the component data; the vector wind speed and wind direction are secondary. The indicated values for u and v for the sodar and radar wind profiler in Table 9-4 refer to the components along the antenna axes, and for these instruments, the component comparisons should be performed using calculated values along the antenna axes. Values along the meteorological axes (north/south and east/west) should only be used if evaluating a radiosonde. For the sodar and radar wind profiler, the data quality objective for the vector wind speed and wind direction comparisons should be applied when winds are greater than 2 to 3 ms^{-1}. Note that the values presented in Table 9-5 are based on a number of studies and were reviewed by several measurement experts participating in an EPA-sponsored workshop on upper-air measurement systems.

Table 9-4.

Suggested data quality objectives for upper-air measurement systems.

Measurement Method	Systematic Difference	Comparability
Radiosonde	p:± 0.5 mb T: ± 0.2°C RH: ± 10% u,v: ± 0.5 to 1 ms^{-1}	P (as height):± 24 m T: ± 0.6°C T_d: ± 3.3°C WS: ± 3.1 ms^{-1} WD: ± 18° to ± 5°[a]
Sodar[b]	u,v: ± 1 ms^{-1} WS: ± 1 ms^{-1} WD: ± 10°	u,v: ± 2 ms^{-1} WS: ± 2 ms^{-1} WD: ± 30°
Radar wind profiler[b]	u,v: ± 1 ms^{-1} WS: ± 1 ms^{-1} WD: ± 10°	u,v: ± 2 ms^{-1} WS: ± 2 ms^{-1} WD: ± 30°
RASS	±1°C	±1.5°C

[a] Over a WS range from 3 to 21 ms^{-1}.

[b] For wind speeds greater than approximately 2 ms^{-1}.

Comparison results in excess of the data quality objectives do not necessarily mean that the data are invalid. In making this assessment, it is important to understand the reasons for the differences. Reasons may include unusual meteorological conditions, differences due to problems in one or both instruments, or differences due to sampling techniques and data reduction protocols. Both the reasons for and the magnitude of the differences, as well as the anticipated uses of the data, should be considered in determining whether the data quality objectives are met. This assessment should be part of the QA protocol.

Data completeness for radiosonde sounding systems is usually not significantly affected by outside environmental conditions such as high winds, precipitation, or atmospheric stability. However, environmental factors can have a significant effect on the rate of data capture for remote sensing systems.

9.4 Siting and Exposure

Siting and exposure issues related to radiosonde sounding systems, sodar, radar wind profiler, and RASS meteorological measurement systems are addressed in this section.

Careful planning should accompany the siting of upper-air measurement systems, since siting and exposure directly affect the quality of the data. The complexities of ground based remote sensing devices provide a challenge for the user to balance the conditions favorable for

the technology with the availability of sites and the overall data collection goals of the program. Site selection may benefit from the experience of vendors or users of the type of instrument to be installed. Additional information on siting can be found in reference [2]. Listed below are some key issues to consider in siting upper-air systems.

- **Representative location.** Sites should be located where upper-air data are needed to characterize the meteorological features important to meeting the program objectives. Panoramic photographs should be taken of the site to aid in the evaluation of the data and preparation of the monitoring plan. Data collected at sites in regions with local geographic features such as canyons, deep valleys, etc., may be unrepresentative of the surrounding area and should be avoided, unless such data are needed to resolve the local meteorological conditions. Measurements made in complex terrain may be representative of a much smaller geographical area than those made in simple homogeneous terrain. See reference [101] for a discussion of the influence of terrain on siting and exposure of meteorological instrumentation.

- **Site logistics.**

  - Adequate power should be available for the instrument system as well as an environmentally controlled shelter that houses system electronics, and data storage and communication devices.

  - The site should be in a safe, well lit, secure area with level terrain, sufficient drainage, and clear of obstacles. The site should allow adequate room for additional equipment that may be required for calibrations, audits, or supplementary measurements.

  - A fence should be installed around the equipment and shelter to provide security, and appropriate warning signs should be posted as needed to alert people to the presence of the equipment.

  - A remote data communications link (e.g., dedicated leased line, standard dial-up modem line, or a cellular telephone link) should be installed at the monitoring site. It is recommended that a 9600 baud or higher line be established to facilitate rapid data transfer and uploading and downloading of information. A site in a remote location with no communication capabilities may collect valid data, but if the system goes down it may not be discovered until the next time the site is visited.

- **Collocation with surface meteorological measurements.** Several advantages can be gained by locating an upper-air site with or near an existing meteorological monitoring station. For instance, collocated data can be used for data validation purposes and for performing reasonableness checks (e.g., do surface winds roughly agree with near-surface upper-air winds, surface temperatures with near-surface RASS measurements). Existing shelter, power, and personnel could also be used for operating the upper-air instrument. Additional surface meteorological measurements of wind speed, wind direction, temperature and humidity are recommended. The height of the wind sensors will depend on the terrain. In homogeneous terrain, wind data collected at a height of 10 m may be sufficient.

- **Instrument noise.** Sodar and RASS generate noise that can disturb nearby neighbors. Depending on the type of sodar or RASS instrument, power level, frequency, acoustic shielding around the system, and atmospheric conditions, the transmitted pulse can be heard from tens of meters up to a kilometer away. An optimum site is one that is isolated from acoustically sensitive receptors **[102]**.

- **Passive interference/noise sources**. Objects such as stands of trees, buildings or tall stacks, power lines, towers, guy wires, vehicles, birds, or aircraft can reflect sodar or radar transmit pulses and contaminate the data. Not all sites can be free of such objects, but an optimum site should be selected to minimize the effects of such obstacles. If potential reflective "targets" are present at an otherwise acceptable site, the beams of the instrument should be aimed away from the reflective objects. In the case of sodars, locating the antennas so that there are no direct reflections from objects will help minimize potential contamination. In the case of the radar profiler, it is best to aim the antennas away from the object and orient a phased array antenna's corners so they are pointing toward the objects. As a rule of thumb, sites with numerous objects taller than about 15° above the horizon should be avoided. The manufacturers of the remote sensing equipment should be contacted regarding software that may be available to identify and minimize the effects of these passive noise sources.

- **Active interference/noise sources.** For sodars, noise sources such as air conditioners, roadways, industrial facilities, animals, and insects will degrade the performance of sodar systems **[102]**. If proximity to such sources cannot be avoided, then additional acoustic shielding may help minimize the potentially adverse effects on the data. In general, noise levels below 50 decibels (dBA) are considered to be representative of a quiet site, while levels above 60 dBA are characteristic of a noisy site. For radar wind profilers and RASS, radio frequency (RF) sources such as radio communications equipment and cellular telephones may have an adverse effect on performance.

- **Licenses and Ordinances**. Before operating a remote sensor it is recommended that all applicable requirements for operation of equipment be addressed. For example, to operate a radar wind profiler or a RASS, a Federal Communications Commission (FCC) license is required. For radiosonde sounding systems (or other balloon-borne systems), a Federal Aviation Administration (FAA) waiver may be required. Local noise ordinances may limit the operation of sodar or RASS instruments. Some of these requirements may take several months to address and complete.

- **Surveying Candidate Locations.** Prior to final site selection, a survey is recommended to identify audio sources **[103]** and RF sources that may degrade system performance. Additionally, panoramic photographs should be taken to aid in the evaluation of the candidate site and for the preparation of the monitoring plan. As part of the survey, appropriate topographic and other maps should be used to identify other potential sources of interference, such as roadways and airports.

9.5   Installation and Acceptance Testing

This section provides guidance for the installation and acceptance testing of upper-air monitoring systems; similar guidance for in situ sensors is provided in Section 8.2.

The installation period is the optimal time to receive appropriate training in instrument principles, operations, maintenance, and troubleshooting, as well as data interpretation and validation. Meteorological consultants as well as some manufacturers and vendors of meteorological instruments provide these services.

Installation procedures specific to upper-air monitoring systems include the following:

- The latitude, longitude, and elevation of the site should be determined using U.S. Geological Survey (USGS) topographical maps, other detailed maps, or a GPS instrument.

- The orientation of antennas of the sodar, radar profiler, or radio theodolite systems should be defined with respect to true north. One recommended method is to use the solar siting technique [2] . This technique enables determination of true north at any location using a compass (or other pointing device suitable for measuring the azimuth angle to the sun), a computer program, the site latitude and longitude, and accurate local time.

- The site should be documented as follows:

    - Photographs in sufficient increments to create a documented 360° panorama around the antennas should be taken. Additionally, pictures of the antenna installation, shelter and any obstacles that could influence the data should be obtained.

    - Photographs of the instrument, site, shelter, and equipment and computers inside the shelter should be obtained.

    - A detailed site layout diagram that identifies true north and includes the locations of the instrument, shelter, other equipment, etc. should be prepared. An example of such a diagram is shown in Figure 9-4. Additionally, it is recommended that the site layout diagram include the electrical and signal cable layout, and the beam directions of any remote sensor.

    - A vista table that documents the surroundings of the site in 30° increments should be prepared. Vistas for the beam directions, if they are not represented by the 30° views (±5°), should be included. The table should identify any potential passive and active noise sources in each direction, and the approximate distance and elevation angle above the horizon to the objects. An example is shown in Table 9-5.

An acceptance test is used to determine if an instrument performs according to the manufacturer's specifications [2]. Manufacturer's procedures for unpacking, inspection, installation, and system diagnostics should be followed to assure that all components are functioning appropriately. All acceptance-testing activities should be documented in the station log.

Once the system is installed, a final field check is needed to assure that the data are reasonable. This is best performed using collocated meteorological information from towers or other upper-air sensors. In the absence of these data sources, nearby upper-air data from the NWS radiosonde network, the NOAA profiler network, aircraft reports, National Center for Environmental Prediction (NCEP) high resolution mesoscale analyses, or other upper-air data can be used. It is important to have an individual trained in the interpretation of the data perform a thorough review of at least several days of data. This check is not meant to evaluate whether or

not the data meet the manufacturer's data specifications, but is intended to identify problems such as:

•   Component failures

•   Incorrect or improper operating/sampling parameters

•   Antenna azimuth angles specified improperly or incorrectly measured

•   Siting problems (active and passive interfering noise sources)

       Shortly after the installation and startup of an instrument, a system and performance audit should be performed. These audits will provide information for the qualitative and quantitative assessment of the performance of the system, as well as the adequacy of the standard operating procedures used for collection, processing, and validation of the data. To best assure that the data collected is of known quality, and that potential problems are identified early, it is recommended the initial audit be performed within 30 days of the start-up date.
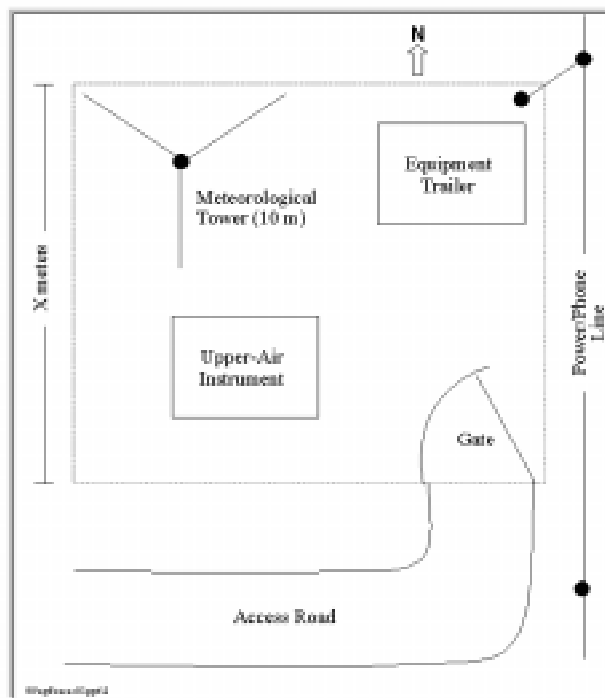

Figure 9-4 Example site layout diagram.

9.6   Quality Assurance and Quality Control

This section provides information on QAQC procedures unique to upper-air measurement systems. Generic material on QAQC procedures for meteorological systems and definitions of terms used in QAQC is presented in Section 8.

With some exceptions (e.g., rawinsonde measurements of pressure, temperature, and humidity) upper-air monitoring systems provide indirect measurements of the meteorological variables used in dispersion modeling. This presents a unique challenge to the quality assurance and quality control (QAQC) of these systems; for example, there is no upper-air counterpart to the bench top calibration of a wind vane. The alternative to the bench-top calibration is a calibration using a collocated transfer standard; this involves locating an identical instrument as close as practical to the instrument being calibrated (see Section 8.3) - again, as with the bench-top procedure, there is no upper-air counterpart to the collocated transfer standard for a wind vane. Similarly, there is no upper-air counter part to the performance audit of a wind vane (as explained in Section 8, calibrations and audits are one and the same as far as "what" takes place; the difference has to do with the independence of the person conducting the audit). Given the inability to conduct a true performance audit, the onus for claims of data validity for most upper-air measurements falls on the systems audit - this, as explained in Section 8.4, is essentially a challenge to the QAPP and provides an overall assessment of the commitment to data validity.

Alternative procedures for calibrations and performance audits of upper-air measurement systems are based on inter-comparisons with other measurement systems - these alternatives are discussed in Sections 9.6.1 (Calibration Methods) and 9.6.2 (Systems and Performance Audits).

Before discussing quality assurance programs, it is useful to explain the difference between quality control (QC) and quality assurance (QA). For the purposes of this document, QC refers to the operational procedures used to ensure that a measurement process is working properly. QC procedures include periodic instrument calibrations, site checks, data examination for reasonableness, and data validation. QC procedures produce quantitative documentation upon which claims of accuracy can be based. QA refers to all the planned or systematic actions necessary to provide adequate confidence that the entire measurement process is producing data that meets the data quality objectives established for a monitoring program. These actions include routine evaluation of how the QC procedures are implemented (system audits) and assessments of instrument performance (performance audits). Summarized below are details on the preparation of a Quality Assurance Project Plan (QAPP) and key elements that are unique to upper-air measurement methods.

Table 9-5

Example site vista table

VISTA, ORIENTATION, AND LEVEL AUDIT RECORD			
Date:	January 3, 1996	Site Name:	Site 5
Key Person:	John Sitetech	Project:	ABC
Instrument:	Radar Wind Profiler	Latitude:	31°10'25"
Model Number:	GEN-1500	Longitude:	91°15'33"
Serial Number:	1234	Elevation:	172 m
Software version:	3.95		
Rotation angle		Direction	
System:	147° true	Beam 1:	146°
Measured:	146° true	Beam 2:	236°
Difference:	1°		
		Firing order:	W, beam 1, beam 2
Array Level:	< 0.5°	Declination:	11° east (solar verification)

Azimuth Angle (deg.)		Terrain Elevation Angle (deg.)	Features/Distance
Magnetic	True		
--	0	12	Buildings and power lines at ~ 300 m.
--	30	19	Stack at 150-200 m.
--	60	22	Power pole at 10 m, < 5° beyond.
--	90	4	Low trees and bushes at 10 m.
--	120	15	Power lines at 200-300 m
--	150	4	Trees at 30-40 m.
----	180	0	Looking out over the lake.
--	240	< 2	Looking out over the lake, can see land.
--	270	< 2	Looking out over the lake, can see land.
--	300	3	Trees and telephone pole at 100 m.
--	330	14	Light pole at 25 m. Buildings at ~250 m.

9.6.1   Calibration Methods

A calibration involves measuring the conformance to or discrepancy from a specification for an instrument and an adjustment of the instrument to conform to the specification. In this sense, other than directional alignment checks, a true calibration of the upper-air instruments described in this document is difficult. Due to differences in measurement techniques and sources of meteorological variability, direct comparison with data from other measurement platforms is not adequate for a calibration. Instead, a calibration of these sensors consists of test signals and diagnostic checks that are used to verify that the electronics and individual components of a system are working properly. Results from these calibrations should not be used to adjust any data. All calibrations should be documented in the station log.

System calibration and diagnostic checks be performed at six month intervals, or in accordance with the manufacturer's recommendations, whichever is more frequent. The alignment of remote sensing antennas, referenced to true north, should be verified at six month intervals. Generic guidance and definitions of terms related to calibrations is provided in Section 8.3.

Radiosonde Sounding Systems For radiosonde sounding systems, the primary calibration that is required is to obtain an accurate surface pressure reading using a barometer that is regularly calibrated and periodically audited. This pressure reading is used to determine if an offset needs to be applied to the radiosonde pressure data. If an offset is needed, the data systems of the commercially available instruments will make the adjustment automatically. It is also useful to obtain surface readings of temperature and atmospheric moisture using a psychrometer or similar instrument. These data can be used to provide a reality check on the radiosonde measurements. This check can be performed using data from a nearby tower. A more robust check can be made by placing the sonde in a ventilated chamber and taking readings that are then compared to temperature and moisture measurements made in the chamber using independent sensors. The alignment of the theodolite should be validated against the reference marker that was installed at the time of system setup.

Sodar Recent advances in instrumentation for auditing of sodar instruments **[104]** have led to the development of a transponder that can simulate a variety of acoustic Doppler shifted signals on certain sodars. This instrument can be used to verify the calibration of the sodar's total system electronics and, in turn, validate the overall system operation in terms of wind speed and altitude calculations. However, such a check should not be considered a "true" calibration of the system since it does not consider other factors that can affect data recovery. These factors include the system signal-to-noise ratio, receiver amplification levels, antenna speaker element performance, beam steering and beam forming for phased-array systems, and overall system electronic noise.

Radar Wind Profilers and RASS A transponding system for radar does not yet exist, but the feasibility of such a system is being explored. Therefore, there is no simple means at present of verifying the accuracy of the Doppler shifted signals in the field other than to perform a comparison with some other measurement system, as described later in this section. Instead, calibrations of radar wind profiler and RASS systems are performed and checked at the system component level. These checks should be performed in accordance with the manufacturer's

recommendations. Like some sodar systems, the radar systems use both software and hardware diagnostics to check the system components.

9.6.2   System and Performance Audits

Audits of upper-air instrumentation to verify their proper operation pose some interesting challenges. While system audits can be performed using traditional system checks and alignment and orientation techniques, performance audits of some instruments require unique, and sometimes expensive procedures. In particular, unlike surface meteorological instrumentation, the upper-air systems cannot be challenged using known inputs such as rates of rotation, orientation directions, or temperature baths. Recommended techniques for both system and performance audits of the upper-air instruments are described below. These techniques have been categorized into system audit checks and performance audit procedures for radiosonde sounding systems, radar wind profilers, sodars, and RASS.

9.6.2.1 Systems Audit

System audits of an upper-air station should include a complete review of the QAPP, any monitoring plan for the station, and the station's standard operating procedures. The system audit will determine if the procedures identified in these plans are followed during station operation. Deviations from the plans should be noted and an assessment made as to what effect the deviation may have on data quality. To ensure consistency in the system audits, a checklist should be used. System audits should be conducted at the beginning of the monitoring program and annually thereafter.

<u>Radiosonde Sounding Systems</u> For radiosonde sounding systems, an entire launch cycle should be observed to ensure that the site technician is following the appropriate procedures. The cycle begins with the arrival of the operator at the site and ends with completion of the sounding and securing of the station. The following items should be checked:

- Ground station initialization procedures should be reviewed to ensure proper setup.

- Sonde initialization procedures should be reviewed to verify that the sonde has been properly calibrated.

- Balloon inflation should be checked to ensure an appropriate ascent rate.

- Proper and secure attachment of sonde to balloon should be verified.

- Orientation of the radio theodolite antenna should be checked, using solar sitings when possible. The antenna alignment should be maintained within $\pm 2°$.

- The vertical angle of the radio theodolite antenna should be checked and should be within $\pm 0.5°$.

- Data acquisition procedures should be reviewed and a sample of the acquired data should be inspected.

- Data archiving and backup procedures should be reviewed.

- Flight termination and system shutdown procedures should be reviewed.

- Preventive maintenance procedures should be reviewed and their implementation should be checked.

- Data processing and validation procedures should be reviewed to ensure that questionable data are appropriately flagged and that processing algorithms do not excessively smooth the data.

- Data from several representative launches should be reviewed for reasonableness and consistency.

- Station logbooks, checklists, and calibration forms should be reviewed for completeness and content to assure that the entries are commensurate with the expectations in the procedures for the site.

Remote Sensing Instrumentation

A routine check of the monitoring station should be performed to ensure that the local technician is following all standard operating procedures (SOPs). In addition, the following items should be checked:

- The antenna and controller interface cables should be inspected for proper connection. If multi-axis antennas are used, this includes checking for the proper connection between the controller and individual antennas.

- Orientation checks should be performed on the individual antennas, or phased-array antenna. The checks should be verified using solar sitings when possible. The measured orientation of the antennas should be compared with the system software settings. The antenna alignment should be maintained within ±2°.

- For multi-axis antennas, the inclination angle, or zenith angle from the vertical, should be verified against the software settings and the manufacturer's recommendations. The measured zenith angle should be within ±0.5° of the software setting in the data system.

- For phased-array antennas, the array should be level within ±0.5° of the horizontal.

- For multi-axis sodar systems, a separate distinct pulse, or pulse train in the case of frequency-coded pulse systems, should be heard from each of the antennas. In a frequency-coded pulse system there may be a sound pattern that can be verified. The instrument manual should be referenced to determined whether there is such a pattern.

- For sodar systems, general noise levels should be measured, in dBA, to assess the ambient conditions and their potential influence on the performance of the sodar.

- The vista table for the site (see Section 9.5) should be reviewed. If a table is not available then one should be prepared.

- The electronic systems and data acquisition software should be checked to ensure that the instruments are operating in the proper mode and that the data being collected are those specified by the SOPs.

- Station logbooks, checklists, and calibration forms should be reviewed for completeness and content to assure that the entries are commensurate with the expectations in the procedures for the site.

- The site operator should be interviewed to determine his/her knowledge of system operation, maintenance, and proficiency in the performance of quality control checks.

- The antenna enclosures should be inspected for structural integrity that may cause failures as well as for any signs of debris that may cause drainage problems in the event of rain or snow.

- Preventive maintenance procedures should be reviewed for adequacy and implementation.

- The time clocks on the data acquisition systems should be checked and compared to a standard of ±2 minutes.

- The data processing procedures and the methods for processing the data from sub-hourly to hourly intervals should be reviewed for appropriateness.

- Data collected over a multi-day period (e.g., 2-3 days) should be reviewed for reasonableness and consistency. The review should include vertical consistency within given profiles and temporal consistency from period to period. For radar wind profilers and sodar, special attention should be given to the possibility of contamination of the data by passive or active noise sources.

9.6.2.2 Performance Audit and Comparison Procedures

Performance audits should be conducted at the beginning of the monitoring program and annually thereafter. A final audit should be conducted at the conclusion of the monitoring program. An overview of the recommended procedures for performance auditing is provided below.

Radiosondes Performance auditing of radiosonde sounding systems presents a unique challenge in that the instrument is used only once and is rarely recovered. Therefore, a performance audit of a single sonde provides little value in assessing overall system performance. The recommended approach is to audit only the instruments that are used to provide ground truth data for the radiosondes prior to launch (thermometer, relative humidity sensor, psychrometer, barometer, etc.). The reference instruments used to audit the site instruments should be traceable to a known standard. Details on these audit methods can be found in reference **[2]**.

In addition, a qualitative assessment of the direction and speed of balloon travel should be made during an observed launch for comparison with the computed wind measurements. An alternative approach is to attach a second sonde package to the balloon, track it from an independent ground station, and compare the results of the two systems. An optical tracking system is adequate for this type of comparison.

Remote Sensing Instrumentation Methods for performance audits and data comparisons of remote sensing instrumentation have been under development for a number of years. Only recently has interim guidance reference **[2]** been released to help standardize performance audit methods. Even with the release of that guidance, there are still a number of areas undergoing

development. Recommended procedures for performance audits and data comparisons of remote sensors which are presented below typically incorporate inter-comparison checks. If inter-comparison checks are used, a quick review of the datasets should be performed before dismantling the comparison system.

Sodar. The performance audit is used to establish confidence in the ability of the sodar to accurately measure winds. A performance audit of a system typically introduces a known value into the sensor and evaluates the sensor response. It may not be possible to perform this type of audit for all types of sodar instruments. In this case, a comparison between the sodar and another measurement system of known accuracy should be performed to establish the reasonableness of the sodar data. With any of the audit or comparison methods, the evaluation of the data should be performed on a component specific basis that corresponds to the sodar beam directions. Any of the following approaches may be considered in the sodar performance evaluation.

- Comparison with data from an adjacent tall tower. Using this approach, conventional surface meteorological measurements from sensors mounted on tall towers (at elevations within the operating range of the sodar) are compared with the sodar data. This method should only be used if the tall tower is an existing part of a monitoring program and its measurements are valid and representative of the sodar location. At least 24 hours of data should be compared. The tower data should be time averaged to correspond to the sodar averaging interval and the comparisons should be made on a component basis. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.

- Comparison with data from another sodar. This comparison uses two sodars operating on different frequencies. The comparison sodar should be located in an area that will allow it to collect data that is representative of the site sodar measurements. At least 24 hours of data should be collected for the comparison. If the measurement levels of the two sodars differ, the comparison sodar data should be volume averaged to correspond with the site sodar. Additionally, the comparison sodar time averaging should correspond to the site sodar. As with the adjacent tall tower, the comparison should be performed on a component basis. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.

- Comparison with radiosonde data. This comparison uses data obtained from a radiosonde carried aloft by a free-flight, slow-rise balloon. The balloon should be inflated so the ascent rate is about 2 ms^{-1}. This will provide the appropriate resolution for the comparison data, within the boundary layer. The wind data should be volume averaged to correspond with the sodar data and the comparisons should be made on a component as well as a total vector basis. The launch times should be selected to avoid periods of changing meteorological conditions. For example, evaluation of the comparison data should recognize the potential differences due to differences in both the spatial and temporal resolution of the measurements (i.e., the instantaneous data collected by the radiosonde as compared with the time averaged data collected by the sodar). This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.

- Comparison with tethersonde data. The tethersonde comparison is performed using single or multi-sonde systems. Using this approach, a tethered balloon is used to lift the

sonde(s) to altitude(s) corresponding with the sodar measurement levels. This method should collect data at one or more layers appropriate to the program objectives. At a minimum, data corresponding to the equivalent of five sodar averaging periods should be collected at each altitude. Multiple altitudes can be collected simultaneously using a multi-sonde system with two or more sondes. The individual sonde readings should be processed into components that correspond to the sodar beam directions and then time averaged to correspond to the sodar averaging period. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.

- Comparison with data from an anemometer kite. This measurement system is suitable in relatively high wind speed conditions that would preclude the use of a tethersonde. The kite anemometer consists of a small sled type kite attached to a calibrated spring gauge. Horizontal wind speeds are determined from the pull of the kite on the spring gauge. The altitude of the kite (i.e. the height of the measured wind) is determined from the elevation angle and the distance to the kite. The wind direction is determined by measuring the azimuth angle to the kite. At a minimum, data corresponding to the equivalent of five sodar averaging periods should be collected at a level appropriate to the monitoring program objectives. The wind speed and kite azimuth and elevation readings should be taken every minute. The individual readings should be processed into components that correspond to the sodar beam directions and then time averaged to correspond to the sodar averaging period. This comparison will provide an overall evaluation of the sodar performance as well as a means for detecting potential active and passive noise sources.

- Use of a pulse transponding system. A pulse transponding system provides a means of testing the sodar system processing electronics for accuracy through the interpretation of simulated Doppler shifted signals at known time intervals [104]. This method can be considered an audit rather than a comparison because it provides a signal input equivalent to a known wind speed, wind direction and altitude to test the response of a sodar system. At least three averaging periods of transponder data should be collected with the sodar in its normal operating mode. Depending on the sodar configuration, this method along with an evaluation of the internal consistency of the sodar data to identify potential passive and active noise sources, may serve as the performance audit without the need of further comparisons. In the case of phased array sodars, an additional comparison is needed to verify proper beam steering. This comparison may be performed using any of the methods above. For this check, three sodar averaging periods at a single level are sufficient. It should be noted that current transponder technology is limited to sodars with three beams.

Radar Wind Profilers. At present, the performance of radar wind profilers can only be evaluated by comparison to collocated or nearby upper-air measurements. Various types of comparison instruments can be used including tall towers, sodar, radiosonde sounding systems, and tethersondes. A tethersonde may be used, but care should be taken to ensure that it does not interfere with the radar operation. Since it is important to have confidence in the reference instrument, an independent verification of operation of the reference instrument should also be obtained. If using a sodar or a radiosonde sounding system, the procedures outlined above should be followed to ensure acceptable operation of the system. If data from an adjacent tower are used, then it is recommended that the quality of the tower-based data be established. The

comparison methods should follow those described for sodars above. Where RASS acoustic sources may interfere with the comparison sodar operation, care should be taken to identify potentially contaminated data.

RASS. Like the radar wind profiler, the evaluation of a RASS relies on a comparison to a reference instrument. The recommended method is to use a radiosonde sounding system to measure the variables needed to calculate virtual temperature (i.e., pressure, temperature, and humidity). Sufficient soundings should be made for comparisons during different times of the day to evaluate the performance of the system under different meteorological conditions. Data collected from the sonde should be volume averaged into intervals consistent with the RASS averaging volumes, and the values should be compared on a level-by-level and overall basis.

9.6.3   Standard Operating Procedures

Standard operating procedures (SOPs) should be developed that are specific to the operations at a given site. The purpose of an SOP is to spell out operating and QC procedures with the ultimate goal of maximizing data quality and data capture rates. Operations should be performed according to a set of well defined, written SOPs with all actions documented in logs and on prepared forms. SOPs should be written in such a way that if problems are encountered, instructions are provided on actions to be taken. At a minimum, SOPs should address the following issues:

- Installation, setup, and checkout

- Site operations and calibrations

- Operational checks and preventive maintenance

- Data collection protocols

- Data validation steps

- Data archiving

9.6.4   Operational Checks and Preventive Maintenance

Like all monitoring equipment, upper-air instruments require various operational checks and routine preventive maintenance. The instrument maintenance manuals should be consulted to determine which checks to perform and their recommended frequency. The quality and quantity of data obtained will be directly proportional to the care taken in ensuring that the system is routinely and adequately maintained. The site technicians who will perform preventive and emergency maintenance should be identified. The site technicians serve a crucial role in producing high quality data and thus should receive sufficient training and instruction on how to maintain the equipment. Some general issues related to operational checks and preventive maintenance should be addressed in the QAPP, including:

- Identification of the components to be checked and replaced

- Development of procedures and checklists to conduct preventive maintenance

- Establishment of a schedule for checks and preventive maintenance

- Identification of persons (and alternates) who will perform the checks and maintenance

- Development of procedures for maintaining spare components that need frequent replacement

Listed below are some key items to be included in the operational checklists for each of the different types of instrumentation. The list is by no means complete, but should serve as a starting point for developing a more thorough set of instrumentation checks.

- Safety equipment (first aid kit, fire extinguisher) should be inventoried and checked.

- After severe or inclement weather, the site should be visited and the shelter and equipment should be inspected.

- Computers should be routinely monitored to assure adequate disk space is available, and diagnosed to ensure integrity of the disk.

- A visual inspection of the site, shelter, instrument and its components should be made.

- Data should be backed up on a routine basis.

- If the remote sensors are operated during the winter, procedures for snow and ice removal should be developed and implemented, as needed.

- The clock time of the instruments should be monitored, and a schedule for updating the clocks established based on the timekeeping ability of the instrument.

- The antenna level and orientation of sodar, radar, RASS, and radio theodolite radiosonde systems should be verified periodically.

- The inside of the antennas/enclosures of the sodar, radar and RASS systems should be inspected and any leaves, dust, animals, insects, snow, ice, or other materials removed. Since the antennas are open to precipitation, drain holes are provided to allow water to pass through the bottom of the antennas. These holes should be periodically inspected and cleaned.

- Cables and guy wires securing the equipment should be checked to ensure that they are tight and in good condition.

- Antenna cables and connections should be inspected for signs of damage due to normal wear, moisture, or animal activities.

- For sodar systems, the site technician(s) should listen to assure that the system is transmitting on all axes and in the correct firing sequence. For three-axis systems, this is accomplished by listening to each antenna. For phased-array systems, this can be accomplished by standing away from the antenna in the direction of each beam and listening for relatively stronger pulses.

- The integrity of any acoustic enclosures and acoustic-absorbing materials should be inspected. Weathering of these items will degrade the acoustic sealing properties of the enclosure and reduce the performance.

- For a radar profiler with RASS, acoustic levels from the sound sources should be measured using a sound meter (ear protection is required) and readings should be compared with manufacturer's guidelines.

All operational checks and preventive maintenance activities should be recorded in logs and/or on appropriate checklists, (electronic and/or paper) which will become part of the documentation that describes and defends the overall quality of the data produced.

9.6.5   Corrective Action and Reporting

A corrective action program must have the capability to discern errors or defects at any point in an upper-air monitoring program. It is an essential management tool for coordination, QC, and QA activities. A workable corrective action program must enable identification of problems, and establish procedures for reporting problems to the responsible parties, tracing the problems to the source, planning and implementing measures to correct the problems, maintaining documentation of the results of the corrective process, and resolution of each problem. The overall documentation associated with the corrective action and reporting process will become part of the documentation that describes and defends the overall quality of the data produced. A sample correction form can be found in reference **[65]**.

9.6.6   Common Problems Encountered in Upper-Air Data Collection

Studies performed to date have indicated that the upper-air measurement systems described in this document can reliably and routinely provide high quality meteorological data. However, these are complicated systems, and like all such systems are subject to sources of interference and other problems that can affect data quality. Users should read the instrument manuals to obtain an understanding of potential shortcomings and limitations of these instruments. If any persistent or recurring problems are experienced, the manufacturer or someone knowledgeable about instrument operations should be consulted.

Radiosonde data are susceptible to several problems, including the following:

- **Poor ventilation.** Prior to launch, lack of ventilation of the sonde may result in unrepresentative readings of temperature and relative humidity (and thus dew-point temperature) at or near the surface.

- **Radio frequency (RF) interference.** RF interference may occasionally produce erroneous temperature, dew-point temperature, and relative humidity measurements, which appear as spikes in the data when plotted in a time series or profile plot.

- **Uncertainties in the tracking mechanism.** Uncertainties in a radio theodolite's tracking mechanism may produce unrealistic changes in the wind speed and direction, especially when the antenna's elevation angle is less than about $10°$.

- **Tracking problems.** Tracking of radiosondes can be problematic within rainshafts or updrafts/downdrafts associated with thunderstorms.

- **Icing.** When a balloon encounters clouds and precipitation zones where the temperature is below freezing, ice can form on the balloon and cause it to descend. Once the balloon descends below the freezing level, the ice melts and the balloon re-ascends. This causes the balloon to fluctuate up and down around the freezing level, and produces unrepresentative wind and thermodynamic data.

- **Poor radio navigation reception.** Not all sites have good radio navigation reception. If this technique is used to track the radiosonde, poor reception can produce uncertainties in the wind data. Poor reception will not affect the thermodynamic data.

- **Low-level wind problems.** Often the first few data points in a radiosonde wind profile tend to have more uncertainty due to initial tracking procedures or difficulties (see Section 9.1 for more details).

  Sodar data can be rendered problematic by the following:

- **Passive noise sources (also called fixed echo reflections).** Passive noise occurs when nearby obstacles reflect the sodar's transmitted pulse. Depending on atmospheric conditions, wind speed, background noise, and signal processing techniques, the fixed echoes may reduce the velocity measured along a beam(s) or result in a velocity of zero. This problem is generally seen in the resultant winds as a rotation in direction and/or a decrease in speed at the affected altitude. Some manufacturers offer systems that have software designed to detect fixed echoes and effectively reject their influence. To further decrease the effect of the fixed echoes, additional acoustic shielding can be added to the system antenna.

- **Active noise sources (ambient noise interference).** Ambient noise can come from road traffic, fans or air conditioners, animals, insects, strong winds, etc. Loud broad-spectrum noise will decrease the SNR of the sodar and decrease the performance of the system. Careful siting of the instrument will help minimize this problem.

- **Unusually consistent winds at higher altitudes**. Barring meteorological explanations for this phenomenon, the most common cause is a local noise source that is incorrectly interpreted as a "real" Doppler shift. These winds typically occur near the top of the operating range of the sodar. A good means of identifying this problem is to allow the sodar to operate in a listen-only mode, without a transmit pulse, to see if winds are still reported. In some cases it may be necessary to make noise measurements in the specific operating range of the sodar to identify the noise source.

- **Reduced altitude coverage due to debris in the antenna.** In some instances, particularly after a precipitation event, the altitude coverage of the sodar may be significantly reduced due to debris in the antennas. In three axis systems, drain holes may become plugged with leaves or dirt and water, snow, or ice may accumulate in the antenna dishes. Similarly, some of the phased-array antenna systems have the transducers oriented vertically and are open to the environment. Blocked drain holes in the bottom of the transducers may prevent water from draining. Regular maintenance can prevent this type of problem.

- **Precipitation interference.** Precipitation, mostly rain, may affect the data collected by sodars. During rainfall events, the sodar may measure the fall speed of drops, which will produce unrealistic winds. In addition, the sound of the droplets hitting the antenna can increase the ambient noise levels and reduce the altitude coverage.

- **Low signal to noise ratio (SNR).** Conditions that produce low SNR can degrade the performance of a sodar. These conditions can be produced by high background noise, low turbulence and near neutral lapse rate conditions.

Data from radar wind profiler systems can be affected by several problems, including the following:

- **Interference from migrating birds.** Migrating birds can contaminate radar wind profiler signals and produce biases in the wind speed and direction measurements [105]. Birds act as large radar "targets," so that signals from birds overwhelm the weaker atmospheric signals. Consequently, the radar wind profiler measures bird motion instead of, or in addition to, atmospheric motion. Migrating birds have no effect on RASS. Birds generally migrate year-round along preferred flyways, with the peak migrations occurring at night during the spring and fall months [106].

- **Precipitation interference.** Precipitation can affect the data collected by radar profilers operating at 915 MHZ and higher frequencies. During precipitation, the radar profiler measures the fall speed of rain drops or snow flakes. If the fall speeds are highly variable during the averaging period (e.g., convective rainfall), a vertical velocity correction can produce erroneous data.

- **Passive noise sources (ground clutter).** Passive noise interference is produced when a transmitted signal is reflected off an object instead of the atmosphere. The types of objects that reflect radar signals are trees, elevated overpasses, cars, buildings, airplanes, etc. Careful siting of the instrument can minimize the effects of ground clutter on the data. Both software and hardware techniques are also used to reduce the effects of ground clutter. However, under some atmospheric conditions (e.g., strong winds) and at some site locations, ground clutter can produce erroneous data. Data contaminated by ground clutter can be detected as a wind shift or a decrease in wind speed at affected altitudes. Additional information is provided in references [107] and [108].

- **Velocity folding or aliasing.** Velocity folding occurs when the magnitude of the radial component of the true air velocity exceeds the maximum velocity that the instrument is capable of measuring, which is a function of sampling parameters [109]. Folding occurs during very strong winds (>20 m/s) and can be easily identified and flagged by automatic screening checks or during the manual review.

RASS systems are susceptible to several common problems including the following:

- **Vertical velocity correction.** Vertical motions can affect the RASS virtual temperature measurements. As discussed in Section 9.1, virtual temperature is determined by measuring the vertical speed of an upward-propagating sound pulse, which is a combination of the acoustic velocity and the atmospheric vertical velocity. If the atmospheric vertical velocity is non-zero and no correction is made for the vertical motion, it will bias the temperature measurement. As a rule of thumb, a vertical velocity of 1 ms^{-1} can alter a virtual temperature observation by 1.6°C.

- **Potential cold bias.** Recent inter-comparisons between RASS systems and radiosonde sounding systems have shown a bias in the lower sampling altitudes [110]. The RASS virtual temperatures are often slightly cooler (-0.5 to -1.0°C) than the reference radiosonde data. Work is currently underway to address this issue.

9.7   Data Processing and Management (DP&M)

An important component of any upper-air meteorological monitoring program is the processing, QA, management, and archival of the data. Each of these components is briefly discussed in this section and some general recommendations for data processing and management are provided. Additional guidance on data issues is provided in Chapter 8 of this guidance document.

9.7.1   Overview of Data Products

For radiosonde systems, the final data products typically consist of one or more ASCII files that contain the reduced thermodynamic data (pressure, temperature, relative humidity, dewpoint, etc.) and wind speed and wind direction as a function of altitude. Some radiosonde data systems store the thermodynamic information in one data file and the wind information in another, whereas other systems combine the observations into a single data file. Regardless of the approach used, the files containing the reduced wind and thermodynamic observations should be considered the final data products produced by the radiosonde sounding systems. Depending on the type of equipment, additional files may be created that include data reported in formats specifically intended for use by the NWS or other organizations, information on site location, sampling parameters, balloon position, etc. Typically, one set of files is created per sounding, that is, data from multiple soundings are not merged together.

For the remote sensing systems (sodar, radar wind profilers, RASS), the final data products usually consist of one or more ASCII files containing the averaged profiles of winds or virtual temperatures as a function of altitude. Supporting information provided with the reduced data products may include other variables such as horizontal and vertical meteorological velocity components (u, v, w), averaged return power, SNR or some other measure of signal strength, estimates of turbulence parameters (σ_w, σ_θ), mixing depth, etc. Typically one set of files is produced per 24-hour sampling period. These data files should be considered the final data products produced by this class of upper-air monitoring system. Other (lower-level) information generated by these systems may include, for example, the Doppler moment data and raw Doppler spectra. The quantity of information produced by the remote sensing systems usually requires that the lower-level data be stored in a binary format to conserve disk space. These data should be archived for backup purposes and to support post-processing or additional analyses of periods of interest.

9.7.2   Steps in DP&M

Data processing, validation, and management procedures for an upper-air meteorological monitoring program would typically include the following steps, which should be described in the QAPP:

•   Collection and storage on-site (as appropriate) of the "raw" signals from the upper-air sensors, followed by real-time processing of the "raw" data by the data acquisition system to produce reduced, averaged profiles of the meteorological variables. The reduced data are stored on the data acquisition system's computer, usually in one or more ASCII files.

•   Transfer of the reduced data to a central data processing facility at regular intervals (e.g., daily). Once the data are received at the central facility, they should be reviewed by an experienced data technician as soon as possible to verify the operational readiness of the upper-air site. Backup electronic copies of the data should be prepared and maintained on-site and off-site.

Data collected by the remote sensing systems can usually be obtained by polling the data system at a site from the central facility using a personal computer, modem, and standard telecommunications software. Other options that are available for communications with a remote upper-air site include leased-line telephone service, local or wide area network (LAN, WAN) connections, Internet access, and satellite telemetry. For immediate turnaround of radiosonde data, the upper-air operator can transfer the sounding data to the central facility using a personal computer equipped with a modem and communications software. There must be a bulletin board system (BBS) operating at the central facility, or some other means provided to receive the data (e.g., via an Internet access). Alternatively, if a one- or two-day delay is acceptable, the operator can mail the sounding data to the data center.

Please note that the initial review of the data is not very time consuming, but it is an extremely important component of a successful upper-air program. It is at this stage that most problems affecting data quality or data recovery will be detected. If the upper-air data are not reviewed at regular, frequent intervals, the risk of losing valuable information increases. If the data are reviewed frequently, then problems can be detected and corrected quickly, often the same day, thereby minimizing data losses. At a minimum, the operational readiness of an upper-air monitoring site should be checked regularly. Likewise, maintaining backup copies of the data at each stage of processing is extremely important. Backup copies should be kept at the central data processing facility and at a separate, off-site location(s) to ensure that no data are damaged or lost.

•   Additional post-processing is performed as required (e.g., reformatting the data using a different database format than that produced by the data acquisition system) to produce the version of the data that will be subjected to final quality control validation.

•   At this stage, the data are usually said to be at "Level 0" quality control validation, meaning that they are ready for quality control screening and final validation.

•   Quantitative screening of the data can be performed using quality control software to identify outliers or other observations that are possibly in error or otherwise appear questionable.

•   A final review of the data should be performed by an experienced meteorologist who understands the methods used to collect the data and who is knowledgeable about the kinds of meteorological conditions expected to be revealed in the data.

This is the process that brings the data to what is usually referred to as "Level 1" quality control validation, meaning that the data have been subjected to a qualitative (and often quantitative) review by experts to assess the accuracy, completeness, and internal consistency of the data. At this stage, data that have been determined to be in error are usually removed from the database, and quality control flags are assigned to the data values to indicate their validity. It is also at this stage that final calibrations should be applied to the data as necessary, as well as any changes required as the result of the system audits. Additional screening of the data based on

comparisons to other independent data sets may be performed, which is part of the process to bring the data to "Level 2" quality control.

- Some final processing may be necessary to convert the data to the format that will be used to submit the information to the final data archive.

Final documentation should be prepared that summarizes sampling strategies and conditions; describes the results of audits and any actions taken to address issues raised by the audits; identifies any problems that adversely affected data quality and/or completeness; and describes the contents and formats of the database. Typically, a copy (electronic and/or paper) of this documentation accompanies the submittal of the data to the final data archive. Once the above steps are completed, the data are ready to be submitted to the upper-air archive. Several options for creating an archive are available, ranging from a simple repository to complex database management systems (DBMS).

9.7.3 Data Archiving

Maintaining a complete and reliable data archive is an important component of a QAPP. Upper-air instruments, especially remote sensors, produce a large amount of data consisting of raw and reduced data. The amount of data from these upper-air sensors can require in excess of several gigabytes of computer storage space per site per year. A protocol for routinely archiving the data should be established.

Raw data are the most basic data elements from which the final data are produced. Archiving these data is important because at a later date the raw data may need to be reprocessed to account for problems, errors, or calibrations. In addition, future processing algorithms may become available to extract more information from the raw data. Raw data are generally stored on-site and should be archived as part of the operational checks. Data should be stored on convenient and reliable archive media such as diskette, tape, or optical disk. The primary archive should be stored in a central repository at the agency responsible for collecting the data. A second backup of the raw data should be made and stored off-site to ensure a backup if the primary data archive becomes corrupted or destroyed.

Reduced data, which are created from the raw data by averaging, interpolating, or other processing methods, should also be archived. Reduced data include hourly averaged winds and temperatures from remote sensors, and vertically averaged winds and thermodynamic data from radiosonde sounding systems. Data validation is performed on the reduced data to identify and flag erroneous and questionable data. Both the reduced and validated data should be routinely (e.g., weekly or monthly) archived onto digital media, with one copy stored onsite and a second copy stored offsite.

Other supporting information should be archived along with the data such as:

- Site and maintenance logs
- Audit and calibration reports
- Site information
- Log of changes made to the data and the data quality control codes

- Information that future users would need to decode, understand, and use the data

- Surface measurements and other relevant weather data

Data should be retained indefinitely because they are often used for modeling and analysis many years following their collection. Periodically, the integrity of the archive media should be checked to ensure that data will be readable and have not become corrupted. Data should be recycled by transfer from old to new media approximately every 5 to 10 years. If an archive is scheduled to be eliminated, potential users should be notified beforehand so that any important or useful information can be extracted or saved.

9.8 Recommendations for Upper-Air Data Collection

- *Suggested Data Quality Objectives (DOQs) for upper-air measurement systems are given in Table 9-5. DOQs for accuracy should be based on systematic differences; DOQs for precision should be based on the "comparability" statistic; DOQs for completeness should be based on percent data recovery.*

- *Site selection for upper-air measurement systems is best accomplished in consultation with vendors or users with expertise in such systems. Operators and site technicians of upper-air monitoring systems should receive appropriate training prior to or during system shake-down. Training should include instruction in instrument principles, operations, maintenance, troubleshooting, data interpretation and validation.*

- *System calibration and diagnostic checks of upper-air measurement systems should be performed at six month intervals, or in accordance with the manufacturer's recommendations, whichever is more frequent.*

- *Data capture for wind direction and wind speed from a sodar or radar wind profiler is defined somewhat differently than for more conventional instruments. The following definitions and requirements apply to databases generated by these instruments:*

    - An averaging period (e.g., hourly) is considered valid if there are at least three valid levels of data for the period (independent of height).

    - If hourly average data are generated from sub-hourly intervals, the hourly values are considered valid if they consist for at least 30 minutes of valid sub- hourly data.

    - A valid level consists of all of the components needed to generate the horizontal wind vector.

- *Remote sensing data should be reviewed at least weekly and preferably daily to assess the operational status of the system and to ensure that data are valid and reasonable.*

General recommendations for the processing, management, and archival of upper-air meteorological data include:

- *A consistent/standardized database format should be established and maintained, at a minimum for each individual monitoring program..*

- *The data archive should include raw, reduced, and validated data as well as other (low-level) data products, as appropriate (e.g., Doppler spectral moments data).*

- *The upper-air data should be validated to Level 1 before distribution.*

- *The data archive should be routinely backed up and checked for integrity.*

- *A secondary backup of the data should be kept at an alternate location, routinely checked for integrity, and periodically recycled onto new storage media.*

Table 9-1

Operating characteristics of upper-air meteorological monitoring systems.

VARIABLES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Measured	• p, T, RH • Vector winds (WS, WD)	• Vector winds (WS, WD) • u,v,w wind components	• Vector winds (WS, WD) • u,v,w wind components	• Virtual temperature (T_v) • w wind component
Derived	• Altitude • Moisture variables (dewpoint, mixing ratio, vapor pressure, etc.) • Potential temperature • Inversion base, top • Mixing depth	• Mixing depth • Dispersion statistics (σ_θ, σ_w)	• Mixing depth	• Inversion base, top • Mixing depth

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

PERFORMANCE CHARACTERISTICS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Minimum Altitude	10-150 m	10-30 m	90-120 m	90-120 m
Maximum Altitude	5-15 km	0.2-2 km	1.5-4 km	0.5-1.5 km
Vertical Resolution	5-10 m (p, T, RH) 50-100 m (winds)	5-100 m	60-100 m	60-100 m
Temporal Resolution	Integration time 5 sec.-2 min. Resolution: intermittent (time between soundings 1.5-12 hr.)	Integration time: 11-60 min. Resolution: continuous	Integration time 15-60 min. Resolution: continuous	Integration time 5-10 min. Resolution: intermittent (time between profiles 5 min-1 hr.)

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

PERFORMANCE CHARACTERISTICS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Systematic Difference	p: ± 0.5 mb T: ± 0.2°C RH: ± 10% U.V.: ± 0.5 to 1.0 ms^{-1}	WS: ± 0.2 to 1.0 ms^{-1} WD: ± 3-10°	WS: ± 1 ms^{-1} WD: ± 3-10°	± 1°C
Comparability	p (as height): ± 24 m T: ± 0.6°C T_d: ± 3.3°C WS: ± 3.1 ms^{-1} WD: ± 5-18°	WS: ± 0.5 to 2.0 ms^{-1} WD: ± 5-30°	WS: ± 2 ms^{-1} WD: ± 30°	± 1.5°C

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Siting Requirements	• Requires relatively flat area approx. 30x30 m (allow sufficient space to launch balloon). • Absence of tall objects (trees, power lines, towers) that could snag weather balloon.	• Requires relatively flat area approx. 20x20 m (allow space for audit equipment, met tower). • Absence of active noise sources. • Absence of passive noise (clutter) targets. • No neighbors within about 100-500 m (depending on the sodar) who would be bothered by noise.	• Requires relatively flat area approx. 20x20 m (allow space for audit equipment, met tower). • Lack of radar clutter targets extending more than 5° above the horizon in antenna pointing directions; 15° otherwise.	• No neighbors within about 1000 m who would be bothered by noise.

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Siting Logistics	• Balloon inflation shelter (e.g., small shed, tent, etc.) • Small (e.g., 8x12 ft.) equipment shelter, tied down, lightning protection • Security fence • 110/220v, 30 amp power service (usually required for air conditioning) • Communications service for data telemetry, voice. • May require FAA approval for operations at airports. • Instrument set-up can be completed in less than a day.	• Small (e.g., 8x12 ft.) equipment shelter, tied down, lightning protection • Security fence • 110/220v, 30 amp power service (usually required for air conditioning) • Communications service for data telemetry, voice. • Site will require 1-2 days to establish once trailer, power, etc. installed.	• Small (e.g., 8x12 ft.) equipment shelter, tied down, lightning protection. • Security fence • 110/220v, 30 amp power service (usually required for air conditioning) • Communications service for data telemetry, voice. • Site will require 2-3 days to establish once trailer, power, etc. installed.	• Add-on to radar profiler or sodar. No special additional logistical requirements. • Approx. 0.5-1 day needed to install and get operational.
Licensing	N/A	N/A	FCC license required	FCC license required

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Routine Operations	• Intermittent sampling; number of soundings varies with measurement objectives. Typically, one sounding per day near sunrise is a minimum sampling frequency; this will characterize the early morning stable boundary layer. Additional soundings are useful at mid-morning (ABL development), mid-to-late afternoon (full extent of daytime ABL), and at night (nocturnal ABL). • Requires expendables for each sounding (radiosonde, balloon, helium, parachute, light for night operations). • Manned operations; requires an operator for each sounding.	• Continuous sampling • Automated, unmanned • Daily checks of operational status via remote polling.	• Continuous sampling • Automated, unmanned • Daily checks of operational status via remote polling.	• Intermittent sampling every hour, or more often as needed. • Automated, unmanned • Daily checks of operational status via remote polling.

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Maintenance	• Bi-weekly barometer calibration checks • Daily back-ups • Back-up tracking device (e.g., optical theodolite) useful in case primary tracking system fails.	• Routine bi-weekly site inspections, servicing • Monthly on-site backups • Snow, ice removal in winter • Manufacturer-recommended spare parts	• Routine bi-weekly site inspections, servicing • Monthly on-site backups • Snow, ice removal in winter • Manufacturer-recommended spare parts	• Routine bi-weekly site inspections, servicing (follow SOP) • Monthly on-site backups • Snow, ice removal in winter • Manufacturer-recommended spare parts
Ground Truth	• Barometric pressure • T, RH • Radio theodolite oriented to true north, level	• Antenna orientation relative to true north • Antenna level	• Antenna orientation relative to true north • Antenna level	• Acoustic sources level • Antenna level

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
QA	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual performance audit of ground truth instruments (e.g., barometer).	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual intercomparison using complementary upper-air system.	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual intercomparison using complementary upper-air system.	• Acceptance test • Standard operating procedure (SOP) • Routine comparison with 10 m tower data • Annual system audit • Annual intercomparison using complementary upper-air system.
Training	• Operators trained to perform soundings; usually requires a few days of classroom and on-site training. • Final data review should be performed by a meteorologist familiar with the instrument systems used.	• Site technicians trained to service equipment; usually requires 1-2 days of on-site training. • Data processing technician trained to poll site, retrieve data, review operational status, troubleshoot problems. • Final data review should be performed by a meteorologist familiar with the instrument systems used.	• Site technicians trained to service equipment; usually requires 1-2 days of on-site training. • Data processing technician trained to poll site, retrieve data, review operational status, troubleshoot problems. • Final data review should be performed by a meteorologist familiar with the instrument systems used.	• Site technicians trained to service equipment; usually requires 1-2 days of on-site training. • Data processing technician trained to poll site, retrieve data, review operational status, troubleshoot problems. • Final data review should be performed by a meteorologist familiar with the instrument systems used.

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

OPERATIONAL ISSUES	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
Data Processing	• Reduce data on-site, ensure proper operations. • Bring final data to at least Level 1 QC validation (see text). • 100 Kb - 1 Mb/sounding	• Use vertical velocity correction (see text). • Bring final data to at least Level 1 QC validation (see text). • 100 Kb/day	• Use vertical velocity correction (see text). • Bring final data to at least Level 1 QC validation (see text). • 150 Kb-1 Mb /day	• Use vertical velocity correction (see text). • Bring final data to at least Level 1 QC validation (see text). • 20 Kb/day

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

STRENGTHS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
	• *In situ* measurements • Deep profiles, high data recovery rates to extended altitudes. • Measures atmospheric moisture • Data compatible with global upper-air network.	• Samples lower parts of ABL • Continuous • Smaller sample volumes (finer vertical resolution). • Fixed reference frame • Useful in complex terrain to measure winds at plume heights.	• Samples through full extent of ABL • Continuous • Data recovery not affected by high wind speeds. • Performance improves with increasing RH. • Fixed reference frame	• Provides high time resolution of temperature profiles in ABL. • Measures T_v • Fixed reference frame

Table 9-1 (continued)

Operating characteristics of upper-air meteorological monitoring systems.

LIMITATIONS	RADIOSONDE	DOPPLER SODAR	BOUNDARY LAYER RADAR WIND PROFILER	RASS
	• Not continuous • Manned operations • Lowest altitude at which good winds are reported can be 200-300 m above ground level depending on tracking system, signal strength, operator training. • Balloon drifts with wind, producing moving reference frame for measurements. • Wet bulb not as reliable as carbon hygristor for measuring frost point. • Launching problematic during thunderstorms. • Subject to icing. • LORAN radio navigation system being discontinued.	• Altitude coverage may not extend through full depth of daytime ABL. • Altitude coverage may be limited at night due to nocturnal inversion. • Interference from active noise sources. • Interference from precipitation. • High wind speeds reduce altitude coverage. • Performance degrades (lower altitude coverage) with low RH. • Nuisance effects from transmitted noise. • Multiple component statistics such as σ_θ not reliable.	• Interference from precipitation. • Interference from migrating birds. • Lowest altitude sampled ~100 m above ground level. • May be subject to ground clutter. • Larger sample volumes (coarser vertical resolution). • Performance degrades (lower altitude coverage) at low RH.	• T_v may need to be converted to T. • Nuisance effects from transmitted noise. • Altitude coverage may not extend through full depth of daytime ABL. • Error sources exist that can produce biases on the order of 0.5-1° C, which may be corrected during post-processing.

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16. ABSTRACT

      This document provides EPA's guidance for the collection and processing of meteorological data for use in regulatory dispersion modeling and is the basis for the regulatory review of proposed meteorological monitoring plans by the EPA Regions and the States. The document contains comprehensive and detailed guidance for meteorological measurement programs, covering the initial design and siting of a system, through data recording and processing.

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