United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

EPA-450/4-87-013
June 1987

Air

EPA

On-Site Meteorological Program Guidance for Regulatory Modeling Applications

EPA-450/4-87-013

On-Site Meteorological Program Guidance for Regulatory Modeling Applications

U.S. Environmental Protection Agency
Region V, Library
230 South Dearborn Street
Chicago, Illinois 60604

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park NC 27711
June 1987

DISCLAIMER

This report has been reviewed by the Office of Air Quality Planning and Standards, EPA, and approved for publication. Mention of trade names or commercial products is not intended to constitute endorsement or recommendation for use.

PREFACE

This document provides EPA's guidance on the collection and use of on-site meteorological data for regulatory modeling applications. It is intended to guide the EPA Regional Offices and States in reviewing proposed meteorological monitoring plans, and will form the basis for the advice and direction given to applicants by the Regional Offices and States. For ease of reference, recommendations are summarized at the end of each section. If the recommendations in this document are not achievable, then alternate approaches should be developed on a case-by-case basis in conjunction with the Regional Office. While the document has undergone external peer review and may eventually be subject to public comment and formal rule-making action, at this time it does not have regulatory status as does the Guideline on Air Quality Models (Revised). It is likely that the document will undergo further revisions based on the experience gained with applying the procedures contained in the document, and additional peer technical review. It is anticipated that this document will eventually supersede relevent sections of the PSD Monitoring Guidelines and the Guideline on Air Quality Models, and be incorporated by reference into those documents.

ACKNOWLEDGEMENTS

This document was prepared by the On-site Meteorological Data Work Group, formed in December 1985 and chaired by Roger Brode, EPA-OAQPS. Its members and their contributions are as follows: Edward Bennett, NY State DEC, Section 6.6; Roger Brode, EPA-OAQPS, Sections 1.0, 2.0 and 4.0; James Dicke, EPA-OAQPS, Section 5.2; Robert Eskridge, EPA-ASRL, Sections 6.2 and 6.3; Mark Garrison, EPA-Region III, Sections 3.2 and 9.0; John Irwin, EPA-ASRL, Sections 6.1 and 6.4; Michael Koerber, EPA-Region V, Sections 3.1 and 3.3; Thomas Lockhart, Meteorological Standards Institute, Section 8.0; Timothy Method, EPA-Region V, Section 3.4; Stephen Perkins, EPA-Region I, Sections 6.5 and 7.0; and Robert Wilson, EPA-Region X, Sections 5.1 and 8.6, and parts of Sections 8.1, 8.2, and 8.5. Through their internal reviews and numerous discussions, all of the work group members have contributed to shaping the document as a whole. The work group wishes to acknowledge the time and effort of those, both within and outside of EPA, who provided technical review comments on the document. The work group also acknowledges the support and helpful guidance of Joseph A. Tikvart, EPA-OAQPS.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

1.1 Background

The use of on-site meteorological data to support air quality impact analyses has grown steadily over recent years. The impetus for this is provided in part by the guidance contained in "Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD)"[1] which is incorporated in the 1980 PSD regulations[2] in support of the 1977 Amendments to the Clean Air Act. Moreover, it is generally recognized that valid on-site data provide a more accurate characterization of the meteorological conditions affecting the transport and dispersion of pollutants emitted by a source than data from a distant location. Subsequent generations of air quality models may require additional on-site meteorological data to characterize the dispersive properties of the atmosphere. The use of on-site meteorological data can therefore be expected to continue to increase in the future.

The PSD Monitoring Guidelines provide only limited guidance on basic instrument accuracy requirements and quality assurance. The quality assurance aspects of on-site meteorological measurements are discussed more completely in another EPA publication, "Quality Assurance Handbook for Air Pollution Measurement Systems: Volume IV. Meteorological Measurements."[3] However, the Quality Assurance Handbook provides guidance most useful for designing a quality assurance program but does not provide specific procedural recommendations necessary for the actual implementation of a quality assurance program in the field. Additional guidance on the application of on-site meteorological data to air quality dispersion models is contained in EPA's "Guideline on Air Quality Models (Revised)."[4] Other sources of information about on-site meteorological monitoring programs include specific air quality model user's guides, an EPA-sponsored workshop report entitled "On-site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources,"[5] and the American Nuclear Society's "Standard for Determining Meteorological Information at Nuclear Power Sites."[6] The model user's guides provide limited guidance on the collection and preparation of on-site meteorological data for individual models.

1.2 Purpose and Scope

The purpose of this document is to provide relatively specific guidance for developing on-site meteorological measurement programs by:

- Consolidating appropriate guidance into a single document;
- Expanding guidance to fill the gaps between existing documents, e.g., data processing procedures;
- Providing guidance to those users who wish to collect and use on-site meteorological data for air quality modeling analyses consistent with the "Guideline on Air Quality Models (Revised);"
- Providing clear recommendations, where justified and appropriate, regarding specific procedures and methods;
- Anticipating to the extent possible, the meteorological data input needs of future generations of regulatory dispersion models; and
- Emphasizing that quality assured on-site data, when available, are preferred for use in air quality analyses.

On-site refers to the collection of data at the actual site of a source that are representative, in a spatial and temporal sense, of the dispersion conditions for the source. This document makes available comprehensive and detailed guidance for on-site meteorological measurement programs, covering initial design and siting of a system through data processing, up to air quality model input.

1.3 Organization of Document

The document is organized to address the different phases of an on-site meteorological monitoring program in separate sections. Where appropriate, different meteorological variables are treated separately by subsections. For ease of reference, recommendations are summarized at the end of each section. However, the discussions in each section should be read to fully understand the recommendations in their proper context.

Section 2.0 provides general background and instrument design-related information on the various primary meteorological variables, including wind speed, wind direction, temperature, temperature difference, water vapor, precipitation, pressure, radiation, and mixing height. Section 3.0 provides an extensive discussion of siting and exposure considerations, including examination of several special siting situations. Meteorological data recording systems are addressed in Section 4.0, and system performance recommendations are presented in Section 5.0. Section 6.0 addresses meteorological data processing methods, one of the areas where guidance has been most needed and most lacking. The discussion in Section 6.0 includes basic computational methods for primary variables and methods for determining several derived variables. Data reporting and archiving are addressed in Section 7.0, and quality assurance and maintenance are the subjects of Section 8.0. Finally, Section 9.0 provides a discussion of Doppler SODAR which addresses all of these major topics for the particular applications of that instrument system. All references are listed in Section 10.0.

2.0 PRIMARY METEOROLOGICAL VARIABLES

This section provides general background information on instrument design characteristics for the meteorological variables of wind speed, wind direction, temperature, temperature difference, atmospheric water vapor, precipitation, pressure, radiation, and mixing height. These variables are considered primary in that they are generally measured directly and are not dependent on or derived from other variables. Derived variables, such as atmospheric stability category and surface roughness length, are discussed in Section 6.4.

Many systems are available for measuring each of the variables discussed. The most appropriate choice of sensing equipment for a particular situation depends on the application(s) for which the data are to be used. Guided by the performance specifications given in Section 5.0, the individual responsible for designing an on-site meteorological monitoring system must balance several considerations, such as accuracy and responsiveness, durability, purchase price, and maintenance costs. In addition, the costs of carrying out a successful monitoring program do not end with the purchase of the appropriate sensors. Depending on the instrument selected, additional equipment for signal conditioning, recording, and possibly electronic data processing are needed. There are also the labor and equipment costs involved in siting, installation, maintenance and calibration of the equipment, and for review, validation, and processing of the data.

This section focuses on those classes of instruments that are considered best suited for routine on-site monitoring programs, and which generally have had the widest use. Recommendations are summarized at the end of the section. Additional information and illustrations for the instruments described in this section, as well as other types of instrumentation not covered in this document, e.g. sonic anemometers, may be found in the Quality Assurance Handbook, Volume IV,[3] as well as in References 7, 8, 9, and 10.

2.1 Wind Speed

Although wind is a vector quantity and may be considered as a primary variable in itself, it is more common to consider wind speed (the magnitude of the vector) and wind direction (the orientation of the vector) separately as scalar variables. Wind speed determines the amount of initial dilution experienced by a plume, and appears in the denominator of the Gaussian dispersion equation. Wind speed is also used to determine the amount of plume rise and in downwash calculations. Wind speed may also be used, in conjunction with other variables, in the derivation of atmospheric stability categories (Section 6.4.4).

This document considers two main types of rotating anemometers - the cup anemometer and the propeller anemometer. These are the most commonly used anemometers for air quality modeling and analysis purposes. Other types of wind sensing equipment, such as hot-wire anemometers and sonic anemometers, are generally used for specialized purposes beyond the scope of most air pollution modeling and impact analyses, and are therefore not covered in this document. Information on these additional types of wind speed sensors can be found in References 7, 8, 9 and 10. The use of Doppler SODARs to remotely sense wind speed is discussed in Section 9.0.

2.1.1 Cup Anemometers

The rotating cup anemometer consists of usually three, sometimes six, hemispherical or cone-shaped cups mounted symmetrically about a vertical axis of rotation. Originally the sensors used four cups. However, three cups have been shown to apply a more uniform torque around the entire revolution and are now standard.[7] 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.[7]

2.1.2 Vane-oriented and Fixed-mount Propeller Anemometers

The vane-oriented propeller anemometer usually consists of a two, three or four-bladed 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. It is important that the dynamic characteristics of the vane are well matched with those of the propeller.

There are several propeller anemometers which employ light-weight molded plastic or polystyrene foam for the propeller blades to achieve threshold speeds of $\leq$ 0.5 m/s.[7] 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 1.0m, these sensors are also suitable for use in determining the standard deviation of the along-wind fluctuations, sigma-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, sigma-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 total passage of the wind (wind-run) instead of instantaneous wind speeds, and may be used to determine the average wind speed over a given time increment. 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.[7]

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 multipoint 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 for a plume in Gaussian models. The standard deviation of the wind direction or elevation angle fluctuations, sigma theta and sigma phi, respectively, may also be used, in conjunction with wind speed, to derive the atmospheric stability category (Section 6.4.4).

2.2.1 Wind Vanes

The most common instrument for measuring wind direction is the wind vane. Wind vanes come in many different shapes and sizes, some with two plates joined at their forward edges and spread out at an angle (splayed vanes) and others with a single flat plate or perhaps a vertical airfoil. Vanes are commonly constructed from stainless steel, aluminum, or plastic. As with anemometers, care should be taken in selecting a sensor that has a proper balance of durability and sensitivity for a particular application.

The horizontal (azimuth) and vertical (elevation) components of the wind direction can be measured with a bi-directional wind vane (bivane). 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.

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.[7] 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. 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 horizontal (sigma theta) and vertical (sigma phi) wind direction fluctuations can be related to the dispersive capabilities of the atmosphere, in particular, to the dispersion coefficients sigma-y and sigma-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 sigma 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 0-360° 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 sigma theta and sigma phi, 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° in order to calculate sigma data.

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 bouyant plume. The vertical temperature difference is used in calculating plume rise under stable atmosheric conditions, and is also used in determining Monin-Obukhov length, a stability parameter (Section 6.4.5).

2.3.1 Classes of Temperature Sensors

The three main classes of temperature sensors are based on: (1) thermal expansion; (2) resistance change; and (3) thermoelectric properties of various substances as a function of temperature.[7] The alcohol and mercury liquid-in-glass bulb thermometers are common examples of thermal expansion sensors. However, these are of limited value in on-site or remote monitoring networks because they lack the means for automated data recording.

A common type of sensor for on-site meteorological measurement programs is the resistance temperature detector (RTD). 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.[7] "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.[7,10]

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.[7] 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 1 minute for a ventilation rate of 5 m/s.[7,8] Time constants for platinum resistance temperature detectors (RTDs) and for termistors mounted in a typical probe are about 45 seconds. These are adequate response times for on-site 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 identicial aspirated radiation shields with equal exposures.

2.4 Atmospheric Water Vapor

2.4.1 Units of Measurement

The quantity of water vapor in the atmosphere may be expressed in terms of several different units of measurement. These are: (1) vapor pressure; (2) saturation deficit; (3) relative humidity; (4) dew point temperature; (5) specific humidity; (6) mixing ratio; and (7) absolute humidity. All except relative humidity provide a complete specification of the amount of water vapor in the air. Determination of relative humidity requires that ambient temperature and pressure also be known.[9] While no existing EPA regulatory models incorporate water vapor measurements, it may be an important variable in determining impacts from moist sources, such as cooling towers. It is also a useful measurement in validating other variables.

Most on-site meteorological monitoring programs for air quality modeling applications incorporate dew point measurements. Many sensors which provide relative humidity measurements, typically in conjunction with a temperature measurement, are commercially available. The other indicators of atmospheric water vapor are not typically measured.

2.4.2 Types of Instrumentation

The two main types of water vapor sensors available are psychrometers and hygrometers. The psychrometer, which works on the thermodynamic principles involved in the vaporization of water, consists of two thermometers, one with a dry bulb and the other with a wet bulb. While still in use at many observing stations, psychrometers do not lend themselves to remote operation and automated data recording. Because of this they are not generally suitable as a primary instrument for an on-site meteorological monitoring program, but may be useful for providing an independent check.

Some hygrometers work on the basis of the effects that moisture has on various substances, such as hair and various chemicals, through absorption. One such 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. Another water vapor sensor used for on-site meteorological programs is the cooled-mirror hygrometer, which operates on the basis of determining the temperature of an artificially cooled surface (commonly a mirror) at the moment 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 suitable for output to an analog recorder and/or conversion to a digital signal for recording on a magnetic medium and processing. The temperature of the surface is typically measured by a linear thermistor or a platinum RTD. Another type of water vapor sensor that has a relatively fast response time is the thin film capacitor. The water vapor is measured by detecting the change in capacitance of a thin polymer film. Special care is needed when employing water vapor sensors in a dusty or polluted environment.

2.5 Precipitation

Precipitation, like water vapor, is not used by existing EPA regulatory models, but provides useful information for the data review and validation process. It would also be important in considering the effects of wet deposition. The two main classes of precipitation measuring devices suitable for on-site meteorological programs are the tipping bucket rain gage and the weighing rain gage. Both types of gage measure total liquid precipitation. Both types of gage may also be used to measure the precipitation rate, but the tipping bucket is preferable for that application. A third type, the optical rain gage, has not yet been adequately developed for widespread use.

The tipping bucket rain gage is probably the most common type of instrument in use for on-site 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 gage 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 gage 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 gage has the advantage that all forms of precipitation are weighed and recorded as soon as they fall into the gage. No heater is needed to melt the snow, except to prevent snow and ice buildup on the rim of the gage, alleviating the problem of evaporation of snow found with the heated tipping bucket gage. Antifreeze is often used to melt the snow in the bucket. However, the weighing gage requires more frequent tending than the tipping bucket gage, 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 on-site 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. Metalized 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.[7]

2.7 Radiation

Solar radiation and net radiation are related to the stability of the atmosphere. Cloud cover and ceiling height data, taken routinely at National Weather Service stations, provide an indirect estimation of radiation effects, and are used in conjunction with wind speed to derive an atmospheric stability category (Section 6.4.4).

The instrument that is used most frequently to measure solar radiation is a pyranometer. The pyranometer measures direct and diffuse radiation on a horizontal surface. A series of thermojunctions are painted with an optical black paint, and the reference thermojunctions are either white or embedded in the body of the instrument. A temperature difference is generated between the reference and the black thermojunctions. An electrical voltage proportional to the incoming solar radiation energy is produced by this thermopile. A standard optical glass dome over the disk is transparent to wavelengths from about 280 to 2800 nm.[7] Some pyranometers use a silicon photovoltaic cell as a transducer. Filters can be used instead of the clear glass dome in order to measure radiation in different spectral intervals.

Another type of sensor is the net radiometer, which is designed to measure the difference between downward (solar) and upward (terrestrial) radiation, through a horizontal surface. The primary application of a net radiometer would be to determine the daytime and nighttime radiation balance as an indicator of stability.

The last type of direct radiation sensor to be discussed is the pyrheliometer, which measures direct solar radiation at normal incidence. The sensing element is a thermopile. The pyrheliometer is supported by a motor-driven equatorial mount in order to maintain normal incidence.

The amount of opaque cloud cover is visually estimated at National Weather Service stations and is reported as the fraction of sky area (in tenths) obscured by clouds. Ceiling height may be estimated visually by a trained observer or may be measured by a cloud ceilometer. Ceilometers transmit a high intensity light pulse upward and estimate ceiling height by measuring some physical property of the reflected light, such as beam width or travel time. Measurements by ceilometers may be hindered when visibility is poor. Other methods of estimating cloud cover and ceiling height are described in Reference 10.

2.8 Mixing Height

The depth of the mixed layer, or mixing height, is an important variable in EPA regulatory models. The mixing height determines the vertical extent of the dispersion process for releases below the mixing height, while releases above the mixing height are assumed to have no ground-level impacts. Morning and afternoon mixing heights are estimated for selected National Weather Service stations from the vertical temperature profiles observed at 1200 Greenwich Median Time (GMT) and surface temperature measurements.[11] Hourly mixing heights are estimated from the twice-daily mixing height values, sunrise and sunset times, and hourly stability categories by the meteorological preprocessor for EPA regulatory models.[12] The Doppler SODAR provides another method for determining mixing height data that may be applicable on a case-by-case basis. The Doppler SODAR is described in more detail in Section 9.0.

2.9 Recommendations

It is recommended that wind speed be measured using a light weight, low friction, three cup or helicoid propeller anemometer. The performance specifications should satisfy the recommendations in Section 5.0. For climates that experience snow and ice the use of a heater should be considered to protect against freezing up of the instrument. The recommendations for wind direction are similar to those for wind speed. A light weight, low friction wind vane, bivane, or U-V propeller system should be used which meets the performance specifications given in Section 5.0. For systems with back-up analog recorders (see Section 4.0), the wind direction sensor should provide output over a 0° to 540° range to avoid chart "painting" problems for north directions. To protect against icing in cold climates, the use of a heater should also be considered for wind vanes.

It is recommended that temperature and temperature difference 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.

The atmospheric water vapor content should be measured by the dew point temperature using a suitable dew point hygrometer that meets the performance specifications contained in Section 5.0.

The measurement of precipitation should be accomplished through the use of either a weighing gage or a tipping bucket gage. In climates that normally experience snow fall, the gage should be equipped with a heater and a wind shield.

The measurement of atmospheric pressure should be accomplished through the use of an aneroid barometer that provides a signal suitable for digital recording. As with other variables, the pressure sensor should meet the performance specifications contained in Section 5.0.

The instrumentation recommendations for radiation measurements depend on the application of the data. Performance specifications for radiation sensors are contained in Section 5.0. Recommendations for non-routine applications should be made on a case-by-case basis. Cloud cover and ceiling height may be estimated visually by a trained observer as indicators of radiation effects. Ceiling height may also be measured by a ceilometer. Twice daily mixing height data may be obtained from atmospheric soundings and surface temperature data at selected National Weather Service stations, or, in some cases, may be measured by Doppler SODAR (see Section 9.0).

3.0 SITING AND EXPOSURE

The concepts of siting (i.e., horizontal and vertical probe placement) and exposure (i.e., spacing from obstructions) of meteorological instruments and towers are covered in this section for the eight variables of interest. General guidance is provided by variable, followed by discussions of special siting considerations for complex terrain, coastal, and urban sites. As a general rule of thumb, an instrument should be sited away from the influence of obstructions such as buildings and trees, and in such a position that it can make measurements that are representative of the general state of the atmosphere in the area of interest. 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 the standard quality assurance procedures mentioned in Section 8.0, annual site inspections are recommended to verify the siting and exposure of the instruments. Approval for a particular site selection should be obtained from the permit granting agency prior to installation.

3.1 General Guidance

3.1.1 Wind Speed and Wind Direction

3.1.1.1 Probe placement

The standard exposure height of wind instruments over level, open terrain is 10m above the ground.[13] 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.[3,5,6,13]. The slope of the terrain in the vicinity of the site should be taken into account when determining the relative height of the obstruction.[3] 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 10m 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 10m, then additional wind measurements should be made at stack top or 100m, whichever is lower.[4] In cases with stack heights of 200m 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 100m, wind data at heights greater than 100m 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.

3.1.1.2 Obstructions

(a) Buildings

Aerodynamic effects due to buildings and other major structures, such as cooling towers, are discussed in the "Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulations) -Revised,"[14] and "Handbook on Atmospheric Diffusion."[15] If wind instruments must be mounted on a building (or other large structure) due to the lack of suitable open space, then the measurement should be made at sufficient height to avoid the aerodynamic wake area. This height can be determined by 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.[3]

(b) 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.

(c) 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.[1,3,5] 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 (sigma) 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 crossmembers) and above/below horizontal cross-members.[3] 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.[1]

(d) 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_0, is presented in

Section 6.4.2. If an area has a surface roughness length greater than 0.5m, then there may be a need for special siting considerations (see discussion in Sections 3.2 and 3.4).

3.1.1.3 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 10m 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 100m, whichever is lower.[4] In cases with stack heights of 200m or above, the appropriate measurement height should be determined by the Regional Office on a case-by-case basis.

3.1.2 Temperature, Temperature Difference, and Water Vapor

The siting and exposure criteria for the three temperature-related variables are similar and, thus, will be discussed together here. Where important, differences between variables are mentioned. Although water vapor content may be measured in a number of ways, the recommended procedure is to measure dew point temperature, T_d.

3.1.2.1 Probe placement

The recommended vertical heights for probe placement are 2m for temperature and 10m and 2m for temperature difference.[5] Where vertical temperature difference measurements are used in determining stable plume rise, the measurements should be made across the plume rise layer, with a minimum separation of 50m. For sites that experience large amounts of snow, adjustments to the temperature measurement height may be necessary, but the temperature probe should not be above 10m. For analysis of cooling tower impacts, measurements of temperature and dew point 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 3.2.3.

The sensor should be located over an open, level area at least 9m in diameter. The surface should be covered by short grass, or, where grass does not grow, the natural earth surface.[3,13] Instruments should be protected from thermal radiation (from the earth, sun, sky, and any surrounding objects) and adequately ventilated using aspirated shields.[1] Forced aspiration velocity should exceed 3 m/s, except for lithium chloride dew cells which operate best in still air.[3] If louvered shelters are used instead for protection (at ground level only), then they should be oriented with the door facing north. Temperature data obtained from naturally-ventilated shelters will be subject to large errors when wind speeds are light (less than about 3m/s).

Temperature 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).[3] In this case, downward facing aspiration shields are necessary.

3.1.2.2 Obstructions

Temperature sensors should be located at a distance of at least four times the height of any nearby obstruction and at least 30m from large paved areas.[3,16] 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).[3,13]

3.1.2.3 Siting considerations

In siting temperature sensors, care must be taken to preserve the characteristics of the local environment, especially the surface. Recommended measurement heights are 2m for temperature and 10m and 2m for temperature difference. Protection from thermal radiation (with aspirated radiation shields) and significant heat sources and sinks is critical. Siting recommendations are similar for dew point 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.

3.1.3 Precipitation

3.1.3.1 Probe placement

A rain gage should be sited on level ground so the mouth is horizontal and open to the sky.[3] The underlying surface should be covered with short grass or gravel. The height of the opening should be as low as possible (minimum of 30 cm), but should be high enough to avoid splashing in from the ground.

Rain gages mounted on towers should be located above the average level of snow accumulation.[16] In addition, collectors should be heated if necessary to properly measure frozen precipitation.[6]

3.1.3.2 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.[5] 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).[16] 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.[3,13,16]

3.1.3.3 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 gage. 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.

3.1.4 Pressure

On-site measurements of pressure are desirable, but not necessary. The standard atmospheric pressure for the station elevation will often be of sufficient accuracy to represent true pressure for dispersion calculations.[5]

3.1.5 Radiation

3.1.5.1 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.[3] Net radiometers should be mounted about 1m above the ground.[3,5]

3.1.5.2 Obstructions

Pyranometers should be located to avoid obstructions casting a shadow on the sensor at any time. Also, light colored walls and artifical sources of radiation should be avoided.[3,5] Net radiometers should also be located to avoid obstructions to the field of view both upward and downward.[3,5]

3.1.5.3 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.

3.2 Complex Terrain Sites

The regulatory definition of complex terrain can include a wide variety of topographic settings, ranging from a single isolated hill rising out of an otherwise flat plain to very rugged terrain where the terrain exerts a major influence on the local flow, affecting transport and dispersion of the pollutant plume(s) of concern. While terrain features can be considered obstructions to the wind flow and should be avoided, siting decisions must take into account which features of the altered flow should actually be measured, if those features have an effect on the plume.

Because of vertical inhomogeneity in complex terrain, it is more important than in the flat terrain case to take measurements at the level of the plume that is being modeled. Horizontal inhomogeneities caused by channeling and other flow distortions further complicate the siting process. Density-driven downslope and upslope flows, channeling of the flow around terrain obstacles or along the axis of a valley, wind speed-up over the crest of terrain, and lingering stagnant conditions in the bottoms of closed valleys, are but a few of the physical phenomena that can be important in a siting decision.

The ideal siting solution in complex terrain involves siting a tall tower between the source in question and the terrain obstacle of concern. The tower should be tall enough to produce measurements at the level of the plume, and should provide measurements of all variables at several levels.

Other terrain in the area should not be so severe as to affect plume transport in a different manner than what is measured by the tower.

Since there are not many situations where this ideal can be achieved, a siting decision in complex terrain must involve some compromises. The basic choices in siting a meteorological tower in complex terrain include siting one tower, siting multiple towers, or utilizing a Doppler SODAR (see Section 9.0) that would include at least a 10-meter tower and may be supplemented by additional tower measurements. Other components of the siting decision include determining specific tower locations, whether or not a tower can be sited on nearby terrain, and measurement heights. 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:

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

2. 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 nearby or on-site 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.

3. For each required variable, alternative measurement locations and techniques should be examined. Advantages and disadvantages of each technique/location should be considered, utilizing as a starting point the discussions presented above and elsewhere in this document.

4. Optimum network design should be determined by balancing the advantages and disadvantages identified in step 3.

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.

3.2.1 Wind Speed

At a minimum, wind speed should be measured at stack top or 100m, whichever is lower, for plume rise calculations. It is preferable to measure wind speed from a tower located near stack base elevation, however, a tower on nearby terrain may also be used to measure wind speed 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 (which would tend to over-estimate the occurrence of stable conditions) or placed in a location that is subject to streamline compression effects (which 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 siting two or more towers, should be evaluated in consultation with the Regional Office.

A Doppler SODAR has the potential to provide the required measurements without the problems entailed by locating a tower on nearby terrain. SODARs have their own special siting requirements and limitations which are discussed in Section 9.0.

3.2.2 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 upslope or downslope 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.[5] 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.

3.2.3 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 50m 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.

3.3 Coastal Sites

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 10m 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.[5] Further specific measurement requirements will be dictated by the data input needs of a particular model. A report prepared for the Nuclear Regulatory Commission[17] provides a detailed discussion of considerations for conducting meteorological measurement programs at coastal sites. However, due to the lack of any recommended model for EPA regulatory applications that specifically addresses a shoreline source, no specific recommendations are made for the collection of measurements beyond those generally required for a non-coastal, rural source.

3.4 Urban Sites

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 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 to the source in question as possible.

3.5 Recommendations

It is recommended that for non-coastal, flat terrain, rural situations, wind instruments should be located over level, open terrain at a height of 10m 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 100m, whichever is lower. For stack heights of 200m or above the appropriate measurement height should be determined by the Regional Office on a case-by-case basis.

In siting temperature sensors, it is recommended that care be taken to preserve the characteristics of the local environment, especially the surface. Recommended measurement heights are 2m for temperature and 10m and 2m for temperature difference. Protection from thermal radiation (with aspirated radiation shields) and significant heat sources and sinks is critical. If temperature difference is to be used in determining stable plume rise, it should be measured across the plume rise layer. A separation of 50m between the two sensors is preferred for these elevated temperature difference measurements.

Every effort should be made to minimize the wind speed at the mouth opening of a precipitation gage. This should be done by using wind shields where significant snowfall occurs. Radiation measurements should be taken in open areas free of obstructions.

Specific siting recommendations cannot be given to cover all possible situations in complex terrain. The process of siting instruments in complex terrain should begin with defining the variables that are needed for a given application. The process should also include defining what terrain influences are likely to be important, using information from topographic maps in conjunction with preliminary estimates of expected plume height range, and any nearby meteorological data. Alternative measurement locations and techniques should then be identified and an optimum design selected by balancing the advantages and disadvantages of the various options.

Special siting considerations also apply to coastal and urban sites. Multiple sites are often desirable in these situations, but model input limitations usually require selection of a single "best" site for modeling applications. Judgements on siting in these specials situations should be made in consultation with the appropriate Regional Office.

If the siting recommendations in this section cannot be achieved, then alternate approaches should be developed in conjunction with the Regional Office. Approval for a particular site selection should be obtained from the permit granting agency prior to installation of a meteorological monitoring system.

4.0 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 multipoint recorder. The multipoint 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 (non-magnetic) 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 acuqisition 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 data 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%.[5] 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, as discussed in Sections 6.1.2 and 6.1.4, a more frequent sampling rate may be required. If the single-pass processor described by Equations 6.1.4 and 6.1.5 in Section 6.1.2 is used for the wind direction, then the data must be sampled at least once per second to insure that consecutive values do not differ by more than 180 degrees.

The sampling rate for multipoint analog recorders should be at least once per minute. The chart speed selected should permit adequate resolution of the data at the chosen sampling rate.

These recommended sampling rates represent minimum acceptable rates for various applications. The accuracy of the computed values will generally improve with increased sampling rates.

4.6 Recommendations

It is recommended that all systems use a microprocessor-based digital data acquisition system as the primary data recording system, because of the advantages in terms of the speed with which data can be analyzed and the accuracy of the data reduction process. Analog data recording systems may be used as a backup. Where analog data are used, wind speed and wind direction should be of the continuous trace strip chart variety. Other variables may be recorded on multipoint charts. Analog charts used for backup data should provide adequate resolution in the data reduction process to achieve the system accuracies given in Section 5.1.

It is recommended that at least 360 samples be utilized to calculate a standard deviation and at least 60 samples be utilized to calculate an average value, regardless of the averaging period (see Section 6.1.4). For an hourly standard deviation value, the data must therefore be sampled at least once every ten seconds. If data are first combined into 15-minute averages, then the data must be sampled at least once every 2.5 seconds to provide 360 samples during the 15-minute period, even if the four 15-minute values are later combined into an hourly value. If the single-pass processor described by Equations 6.1.4 and 6.1.5 in Section 6.1.2 is used for the wind direction, then the data must be sampled at least once per second. For multipoint analog recorders, the sampling rate per channel should be at least once per minute, and the selected chart speed should permit adequate resolution of the data.

5.0 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.[18] The accuracies recommended for on-site 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.

The accuracy specifications and resolutions provided in Table 5-1 are applicable to the primary measurement system, which is recommended to be a microprocessor-based digital system. For analog systems used as back-up the recommended accuracy limits in Table 5-1 may be increased by 50%. Resolutions for such analog systems should be adequate to maintain the recommended accuracies.

Table 5-1

Recommended System Accuracies and Resolutions

Meteorological Variable	System Accuracy	Measurement Resolution
Wind Speed (horizontal & vertical)	± (0.2 m/s + 5% of observed)	0.1 m/s
Wind Direction (azimuth & elevation)	± 5 degrees	1 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	0.3 mm
Pressure	± 3 mb (0.3 kPa)	0.5 mb
Radiation	± 5% of observed	10 W/m^2
Time	± 5 minutes	-

The averaging times associated with the required accuracies correspond to the averaging times associated with the end use of the data and with the audit methods recommended to evaluate system accuracies.

5.2 Response Characteristics of On-Site Meteorological Sensors

Certain response characteristics of meteorological sensors proposed for on-site monitoring programs must be known to ensure that data on the variables are appropriate for the intended application. For example, an anemometer designed to endure the rigors experienced on an ocean meteorological buoy may be unsuitable for deducing fine scale turbulent structure where accurate response to fluctuations on the order of 0.1 second is essential. Conversely, a sonic anemometer is unnecessary if the data are used only to calculate hourly averages of wind speed and direction for input to a dispersion model.

The following definitions apply for terms commonly associated with instrument response characteristics and the inherent properties of meteorological sensors:

a. Calm. Any average wind speed below the starting threshold of the wind speed or direction sensor, whichever is greater.[6]

b. 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=1 and there is no overshoot in response to sudden changes in wind direction.[19]

c. 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.[20] The delay distance is commonly specified as "50% recovery" using "10° displacement."[3,5]

d. 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., 1 - 1/e, of the increasing step-function change in speed.[20] Distance constant is a characteristic of cup and propeller (rotational) anemometers.

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

f. Threshold (starting speed). The wind speed at which an anemometer or vane first starts to perform within its specifications.[21]

g. Time constant. The time constant is the period that is required for a (temperature) sensor to respond to 63.2%, i.e., 1 - 1/e, of the stepwise 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.

Several publications are available that either contain tabulations of reported sensor response characteristics[19,22] or specify, suggest or recommend values for certain applications[1,3,5,13]. Moreover, many manufacturers are now providing this information for the instruments they produce.[22]

The "Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD)"[1] contains recommendations on meteorological instrumentation for PSD monitoring programs. An EPA workshop report on meteorological instrumentation[5] expands on these recommendations for certain variables.

Further clarification and definition of recommended response characteristics for meteorological instruments sited to provide input to models listed in Appendix A of the Guideline on Air Quality Models (Revised)[4] is warranted. Table 5-2 provides a recapitulation and further development of the response characteristics.

Verifying that a meteorological sensor possesses the recommended response characteristics listed in Table 5-2 can accurately be accomplished only in a laboratory setting and is not recommended at field sites. Acceptance testing, calibrations, audits, operational tests and preventive maintenance will normally provide assurance of satisfactory performance. The manufacturer should provide evidence (see Section 8.0) that the response characteristics of the sensor have been determined according to accepted scientific/technical methods, e.g., ASTM standards.[23]

5.3 Data Recovery

5.3.1 Data Base Considerations

Air quality modeling analyses should be based on as many years of site-specific data as are available.[4] Enough meteorological data should be acquired to ensure that worst-case meteorological conditions are adequately represented in the data base. Although less than one year of data may be sufficient to determine the acceptability of a model for a given application, once the model has been accepted, a full year of data must be used in a PSD analysis.[1] In addition, there should not be any marked correlation between periods of missing data and various meteorological

Table 5-2. Recommended Response Characteristics for Meteorological Sensors

Meteorological Variable	Sensor Specification(s)
A. Wind Speed	
1. Horizontal	Starting Speed $\leq$ 0.5 m/s; Distance Constant $\leq$ 5m
2. Vertical	Starting Speed $\leq$ 0.25 m/s; Distance Constant $\leq$ 5m
B. Wind Direction	Starting Speed $\leq$ 0.5 m/s @ 10° Deflection; Damping Ratio 0.4 to 0.7; Delay Distance $\leq$ 5m
C. Temperature	Time Constant $\leq$ 1 minute
D. Temperature Difference	Time Constant $\leq$ 1 minute
E. Dew Point Temperature	Time Constant $\leq$ 30 minutes; Operating Temperature Range -30°C to +30°C
F. Radiation	
1. Global Sun and Sky	Time Constant $\sim$ 5 sec.; Operating Temperature Range -20°C to +40°C at Specified Accuracy
2. Net Radiation	Time Constant $\leq$ 30 sec.

cycles or occurrence of special meteorological phenomena, e.g., inversion breakups, land and sea breezes, valley channeled flows, stagnations, etc.

5.3.2 Single Meteorological Variable Data Recovery

The operation of an on-site meteorological measurement program must ensure at least 90% valid data retrieval, on an annual basis, for each variable being measured. Less stringent data retrieval requirements, e.g., as low as 80%, may be appropriate for geographically remote instrument sites, but this may require a monitoring program of longer duration if the data are crucial to the analysis. A well-coordinated and carefully executed program of preventive maintenance and frequent data screening and validation is essential to maintaining acceptable recovery rates (see Sections 8.5 and 8.6). Redundant sensors, recorders and data logging systems may also be necessary to achieve an acceptable data base, considering normal outages for calibrations, audits, etc.

5.3.3 Joint Wind and Stability Data Recovery

Valid wind speed and direction together with atmospheric stability data form the input cornerstone for regulatory dispersion models. Thus, the joint recovery rate for model inputs of these data, whether as direct input (wind speed and direction) or as derived values (stability), must be at least 90% on an annual basis.

5.3.4 Handling of Missing Data

Substitution of valid representative data for missing periods to achieve a complete data set for modeling applications may be acceptable in some circumstances, as discussed in Section 6.5. However, substitution to attain the 90% data retrieval recommendation is not acceptable.

5.4 Recommendations

It is recommended that on-site meteorological data systems meet the system accuracies and resolutions given in Table 5-1 and the response characteristics stated in Table 5-2. The accuracies and resolutions apply to the primary measurement system. If an analog system is used for backup, the recommended accuracy limits in Table 5-1 may be increased by 50%. The 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. It is recommended that valid data retrieval rates of 90% be maintained on an annual basis, for each variable being measured, and for joint recovery of wind speed, direction, and atmospheric stability. Guidance on handling missing data periods for modeling applications is provided in Section 6.5.

6.0 METEOROLOGICAL DATA PROCESSING METHODS

This section provides methods for processing of meteorological data and preparing it for input to a regulatory air pollution model. Regulatory models generally require hourly averages of particular meteorological variables, usually including the primary variables of wind speed and wind direction, and the derived variable of atmospheric stability category at a minimum. The stability category is an indicator of the dispersive capacity of the atmosphere. These hourly values may be obtained by averaging samples over an entire hour or by averaging a group of shorter period averages. If the hourly value 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 standard deviation of horizontal wind direction fluctuations, 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 were missing.

The processing of primary meteorological variables, including computations of means and standard deviations, is addressed in Sections 6.1, 6.2 and 6.3. Section 6.4 describes processing methods for several derived meteorological variables that are used in air pollution modeling. Preparation of data for model input is addressed in Section 6.5, and the use and representativeness of off-site data for modeling is the subject of Section 6.6. Recommendations are summarized in Section 6.7.

6.1 Wind Data Processing

This discussion outlines computations for processing wind data. There are several statistics used in meteorology to describe the wind, and they vary according to application. It is assumed that data result from the operation of a cup or propeller and vane instrument system. At a minimum, the horizontal wind direction and speed are available. If the vane is a bivane, then the elevation angle data are also available.

The wind has both an orientation (direction) and a magnitude (speed), and is therefore a vector quantity, but speed and direction can also be treated separately as scalar quantities. Dilution calculations depend on the magnitude and not the direction of the wind vector, and should therefore be based on the scalar mean wind speed. The vector (resultant) mean wind speed should not be used for dilution. In a variable trajectory model or a model that accepts a separate wind speed to predict transport time, the vector mean wind speed may be appropriate. While not in common use, the harmonic mean (scalar) wind speed is also appropriate and may be used for modeling dilution.

In straight-line Gaussian models, the atmospheric transport of effluents should be modeled using the scalar mean wind direction. For microprocessor based systems, unit vector mean wind direction is also acceptable for modeling transport. Use of the wind-speed-weighted vector mean wind direction is not recommended for this application because it will bias the location of the plume toward higher wind speeds, and therefore generally smaller concentrations. However, in a variable trajectory model the vector mean wind direction may be used to model the transport direction. An exception to these recommendations is made for Doppler SODAR systems (Section 9.0), which are designed to calculate the vector mean wind speed and direction. Scalar processing of SODAR data should be employed wherever possible.

6.1.1 Notation

(a) Observed raw data

U_i = horizontal wind speed
A_i = horizontal wind direction, measured clockwise from north, values restricted to between 001 and 360 degrees (inclusive)
W_i = vertical wind speed
E_i = elevation angle of the wind (also called the vertical wind direction)

(b) Scalar wind computations

US = mean horizontal wind speed
UH = harmonic mean wind speed
AS = mean horizontal wind direction
WS = mean vertical wind speed
ES = mean elevation angle (or vertical wind direction)
σ_U = standard deviation of horizontal wind speed fluctuations
σ_A = standard deviation of horizontal wind direction fluctuations
σ_W = standard deviation of the vertical wind speed fluctuations
σ_E = standard deviation of the elevation angle (or vertical wind direction) fluctuations

(c) Vector wind computations

UV = resultant mean horizontal wind speed
AV = resultant mean horizontal wind direction
DV = unit vector mean horizontal wind direction
V_e = mean east-west component of wind (positive toward east)
V_n = mean north-south component of wind (positive toward north)
V_x = mean east-west unit vector component
V_y = mean north-south unit vector component
x,y,z = standard right hand rule coordinate system with x-axis aligned towards the east

6.1.2 Computation

By employing single-pass processing techniques, the formulas presented promote real-time processing of the data as it is collected. Computation of the statistical descriptors of the wind occurs after the data validation checks. During these quality assurance checks, some of the data may be flagged as suspect or invalid. Therefore, the series of observations processed may not consist of consecutive values equally spaced in time. Sporadic loss of data values is acceptable. Long periods of invalid data obscure the interpretation of statistical descriptors of the wind. Specific guidance for handling calms and missing data as model inputs is offered in Sections 6.5.2 and 6.5.3. Data validation recommendations are provided in Section 8.6.

6.1.2.1 Scalar

The scalar mean horizontal wind speed is,

$$US = (1/N) \sum U_i \qquad (6.1.1)$$

where N is the number of valid values. The harmonic mean (scalar) wind speed is,

$$UH = N/ \sum (1/U_i). \qquad (6.1.2)$$

The standard deviation of the horizontal wind speed is,

$$\sigma_U = [(1/N) \sum (U_i^2 - US^2)]^{1/2}. \qquad (6.1.3)$$

The horizontal wind direction is a circular function with values limited to between 001 and 360 degrees. To handle the wind direction scale discontinuity requires some special processing.

If the time interval between observations is short enough (see Section 6.1.4), then the difference, DELTA, between consecutive wind direction observations can be assumed to be less than 180 degrees. In such cases, the mean horizontal wind direction is,

$$AS = (1/N) \sum D_i(i) \tag{6.1.4}$$

where

$$D_i(i) = A_i(i) \text{ for } i=1$$

and

$$D_i(i) = \begin{cases} D_i(i-1) + DELTA + 360 & \text{if } DELTA < -180 \\ D_i(i-1) + DELTA & \text{if } DELTA < 180 \\ D_i(i-1) + DELTA - 360 & \text{if } DELTA > 180 \end{cases}$$

$$DELTA = A_i(i) - D_i(i-1), \text{ for } i > 1.$$

This procedure should also be used to average four 15-minute average wind directions to obtain an hourly average. The standard deviation of the horizontal wind direction is,

$$\sigma_A = [(1/N) \sum (D_i^2 - AS^2)]^{1/2} \tag{6.1.5}$$

The mean wind direction and the standard deviation have the units of degrees The mean wind direction computed using (6.1.4) may not be between 001 and 360 degrees. If the result is less than 001 degree or greater than 360 degrees, increments of 360 degrees should be added to or subtracted from the answer, as appropriate, until the result is between 001 and 360 degrees.

Cases will arise when the difference in adjacent wind direction observations cannot be assumed to be less than 180 degrees. In such cases, approximation formulas are useful for computing the standard deviation of the horizontal wind direction. Mardia[24] shows that a suitable estimate of the standard deviation (in radian measure) is,

$$\sigma_A = [-2 \ln(R)]^{1/2} \tag{6.1.6}$$

where

$$R = (Sa^2 + Ca^2)^{1/2}$$

$$Sa = (1/N) \sum \sin(A_i)$$

$$Ca = (1/N) \sum \cos(A_i).$$

Several methods for calculating the standard deviation have been compared,[25] and a method which provided excellent results over the entire range of possible standard deviations can be expressed as:[26]

$$\sigma_A = \arcsin(\varepsilon)\ [1. + 0.1547\ \varepsilon^3] \tag{6.1.7}$$

where

$$\varepsilon = [1. - (\overline{\sin(A_i)}^2 + \overline{\cos(A_i)}^2)]^{1/2}.$$

The standard deviation of the vertical wind speed fluctuations is,

$$\sigma_W = [(1/N)\ \sum (W_i^2 - WS^2)]^{1/2} \tag{6.1.8}$$

$$WS = (1/N)\ \sum W_i.$$

Similarly, the standard deviation of the vertical wind direction fluctuations is,

$$\sigma_E = [(1/N)\ \sum (E_i^2 - ES^2)]^{1/2} \tag{6.1.9}$$

$$ES = (1/N)\ \sum E_i.$$

To minimize the effects of meander under light wind speed conditions on σ_A for the hour, it is recommended that four 15-minute values be computed and averaged as follows:

$$\sigma_A(1\text{-hr}) = [(\sigma_{A15}^2 + \sigma_{A30}^2 + \sigma_{A45}^2 + \sigma_{A60}^2)/4]^{1/2} \tag{6.1.10}$$

6.1.2.2 Vector

From the sequence of N observations of A_i and U_i, the mean east-west, V_e, and north-south, V_n, components of the wind are,

$$V_e = -(1/N)\ \sum U_i \sin(A_i) \tag{6.1.11}$$

$$V_n = -(1/N)\ \sum U_i \cos(A_i). \tag{6.1.12}$$

The resultant mean wind speed and direction are,

$$UV = (V_e^2 + V_n^2)^{1/2} \qquad (6.1.13)$$

$$AV = \mathrm{ArcTan}(V_e/V_n) + \mathrm{FLOW} \qquad (6.1.14)$$

where

$$\mathrm{FLOW} = \begin{cases} +180^{o} & \mathrm{ArcTan}(V_e/V_n) < 180^{o} \\ -180^{o} & \mathrm{ArcTan}(V_e/V_n) > 180^{o} \end{cases}$$

Equation 6.1.14 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,

$\mathrm{ATAN}(V_e/V_n)$

or $\mathrm{ATAN2}(V_e, V_n)$.

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

6.1.2.3 Unit vector

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, U_i. Equations 6.1.11 and 6.1.12 become

$$V_x = -(1/N) \sum \sin(A_i) \qquad (6.1.15)$$

$$V_y = -(1/N) \sum \cos(A_i) \qquad (6.1.16)$$

The unit vector mean wind direction is then

$$DV = \mathrm{ArcTan}(V_x/V_y) + \mathrm{FLOW} \qquad (6.1.17)$$

where

$$\mathrm{FLOW} = \begin{cases} +180^\circ & \mathrm{ArcTan}(V_x/V_y) < 180^\circ \\ -180^\circ & \mathrm{ArcTan}(V_x/V_y) > 180^\circ \end{cases}$$

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

6.1.3 Vertical Profiles

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

$$US = UR(Z/ZR)^p \qquad (6.1.18)$$

where

US = the scalar mean wind speed at height Z above ground
UR = the scalar mean wind speed at some reference height ZR, typically this is 10 meters
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 stronger 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 (6.1.18) for p,

$$p = \frac{\ln (US) - \ln (UR)}{\ln (Z) - \ln (ZR)}. \qquad (6.1.19)$$

As discussed by Irwin[27], 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 on-site wind measurements should be stratified by stability and surface roughness. Surface roughness may vary as a *function of wind azimuth and* 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 to heights within the height range and to the season of the wind data 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 as follows:

Stability Category	Urban p value	Rural p value
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 UL represent the wind speed found by linear interpolation and US the "correct" wind speed. Then the fractional error is,

$$FE = (UL - US)/US. \qquad (6.1.18)$$

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

$$ZM = [pZL/(p-1)] - [p/(p-1)](ZL/ZR)^p(ZU-ZL)/A \qquad (6.1.19)$$

$$MAX(FE) = \frac{(ZL/ZR)^p-(ZM/ZR)^p+A(ZM-ZL)/(ZU-ZL)}{(ZM/ZR)^p} \qquad (6.1.20)$$

where

$$A = (ZU/ZR)^p - (ZL/ZR)^p.$$

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

Height interval (meters)	Maximum percentage error (%)	Height (ZM) of maximum error (meters)
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 (6.1.20). Even with this limitation, the methodology is useful for determining the optimum heights to place a limited number of wind sensors. The height ZM represents the optimum height to place a third sensor given the location of the two surrounding sensors.

6.1.4 Sampling Rate

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%.[5] 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 Section 6.1.2.1, a single-pass method is presented to handle the scale discontinuity in making calculations with the horizontal wind direction (Equations 6.1.4 and 6.1.5). It requires the difference between consecutive values to always be less than 180^{o}. To assure this, it is recommended that at least one value be sampled every 1 second. For sampling durations less than 6 minutes when standard deviation calculations are made, increase the sampling rate to maintain at least 360 samples during the period. For instance, for a 3 minute sampling duration, sample one value at least every 0.5 seconds.

6.2 Temperature Data Processing

Atmospheric temperature measurements have three basic uses: (1) as a local measure of air temperature; (2) as a measurement used to determine lapse rates and inversions; and (3) high frequency temperature measurements are taken together with high frequency velocity measurements to calculate the vertical transport of heat near the earth's surface.

Point values of temperature are used in calculating the initial buoyancy flux in plume rise calculations via

$$F = g(T_p - T_e)V/T_p, \quad (6.2.1)$$

where the subscripts p and e indicate plume and environmental values, respectively, and V is the volume flux (Hanna et al).[14] Point values of temperature are also used in converting pollutant concentrations from $g\ kg^{-1}$ to ppm. These are the only two important uses of point values of temperature in air pollution modeling. For these two applications, 15-minute averaged values are the best choice, but hourly averaged values or instantaneous values are acceptable as neither of these calculations are sensitive to small errors in the ambient temperature. The average temperature is calculated by

$$\bar{T} = 1/N \sum T_i \quad (6.2.2)$$

where

$\bar{T}$ = mean temperature

T_i = observed temperature sample

N = number of samples in averaging period

In determining the vertical temperature gradient, ΔT, the relative accuracy and resolution of the thermometers are of critical importance. The measured temperature gradients are used in determining stability parameters such as the bulk Richardson number, the Monin-Obukhov length, etc., which are meaningful only in representing the mean state of the atmosphere.

For this purpose, two matched thermometers are generally located at 2m and 10m above the surface and yield a temperature difference of at most a few degrees Celsius. During the daytime the recommended time averaging period is 15 minutes. The sample time for constructing averages should be long enough for the averages to be statistically stable, but short enough so that diurnal effects are minimal. The rapid changes due to the rising and setting of the sun are minimized by this averaging time. In non-complex terrain during the nighttime hours the structure of the boundary layer and surface layer change more slowly as surface radiative effects dominate convective exchanges of heat. Therefore, during the nighttime a one hour averaging time is sufficient for most applications. The vertical temperature gradient may also be used in determining plume rise during stable atmospheric conditions. In this case, it is preferrable to make the measurement across the plume rise layer. A minimum height separation of 50m is recommended for this application. The temperature difference, ΔT, is then calculated by

$$\Delta T = 1/N \sum \Delta T_i \qquad (6.2.3)$$

The calculation of non-Pasquill stability parameters is discussed briefly in section 6.4.5 and in detail in Paumier et al.[28]

The final use of temperature data is in the measurement of vertical heat flux, H, which may be used in the determination of Monin-Obukhov length. A fast response anemometer and thermometer are operated together to calculate

$$\begin{aligned} H &= \rho\, c_p\, \overline{W'T'} \\ &= \rho\, c_p\, (1/N) \sum (W_i - \overline{W})(T_i - \overline{T}) \\ &= \rho\, c_p\, [(1/N) \sum W_i T_i - (1/N^2)(\sum T_i)(\sum W_i)] \end{aligned} \qquad (6.2.4)$$

where W' and T' are deviations from the mean, W_i and T_i are the measured values, and $\overline{W}$ and $\overline{T}$ are mean values of vertical wind speed and temperature, respectively, ρ is the air density, and c_p is the specific heat of air at constant pressure. The averaging time is usually 15 minutes during daylight hours and 60 minutes at night.

Measurement of the vertical flux of heat is usually done only in research projects because of the expense of the instruments and the complexity of the data analysis procedures. The location of the instruments will depend on the problem being studied and the type and number of instruments being used.

6.3 Data Processing for Other Primary Variables

If digital data are available for dew point, pressure and radiation, 15-minute or hourly averages should be constructed. If digital data are not available, a one-hour point or a one-hour analog average value should be recorded for each of these variables. Precipitation data should be processed to yield a total for every hour.

6.4 Processing Derived Meteorological Variables

This section provides processing recommendations for several derived meteorological variables that are utilized in air pollution modeling. Standard computations of first and second moments (means and standard deviations) of primary meteorological variables are addressed in Sections 6.1 through 6.3.

6.4.1 *Standard Deviation of Vertical Wind Direction*

The standard deviation of the vertical wind direction fluctuations, σ_E, may be used to determine Pasquill stability categories for regulatory models (Section 6.4.4.2). This section discusses approximating σ_E as,

$$\sigma_E = \sigma_W/US \qquad (6.4.1)$$

where

σ_E = standard deviation of the vertical wind direction fluctuations

σ_W = standard deviation of the vertical wind speed fluctuations

US = scalar mean wind speed.

It should be noted that σ_E in this discussion is in radian measure.

Weber et al.[29] report good performance for this approximation for cases when wind speeds are greater than 2 m/sec. The site location was near the Savannah River Laboratory (SRL), which is near Augusta, Georgia. The sampling rate was one value every 0.2 seconds. The sampling duration was 40 minutes. For the 714 cases analyzed, the correlation coefficient (r^2) was 0.99. Least squares regression results suggest a tendency for σ_W/US to underestimate σ_E/US by about 3%.

Deihl[30] analyzed data collected over a one year period. The sampling rate was one value every 10 seconds. The sampling duration was 30 minutes. The study location was in the San Juan Basin near Los Alamos, New Mexico. About 26% of the periods had wind speeds less than 2 m/sec. The approximation of σ_E by σ_W/US was adequate for those cases with wind speeds greater than 2 m/s. The comparison was not as good as with the SRL study. The performance varied depending on the overall turbulence intensity. When the bivane σ_E values were greater than 3^o, there was a slight tendency to underestimate σ_E. When the bivane values of σ_E were less than 3^o, there was an increasing tendency to overestimate σ_E. Overestimates of a factor of two occurred for some of the cases. This was especially true when the bivane σ_E values were less than 1^o.

The correlation of σ_E and σ_W/US markedly decreased for those cases when the wind speed was less than 2 m/sec. For these low wind speed cases, there was a bias to overestimate the value of σ_E by 30% when using σ_W/US.

It is concluded from these studies that σ_E is best approximated by σ_W/US when,

- wind speeds are greater than 2 m/sec, and
- σ_E is greater than 3^o.

Turbulence intensities are minimal during stable nighttime conditions. This is especially true when there are no clouds to retard the radiative cooling at the surface. During such times the winds diminish at the surface and the turbulence intensities are quite low. These are demanding times for any turbulence measuring instrument. During these times, the bivane appears to better respond to the turbulent fluctuations in the vertical than a propeller anemometer.

6.4.2 Surface Roughness Length

The surface roughness length, z_0, forms the lower boundary in diffusion models. In surface layer similarity theories, it is the scaling length for the vertical coordinate. It is also used in adjusting stability category boundaries for vertical and lateral turbulence statistics, σ_E and σ_A (Sections 6.4.4.2 and 6.4.4.3).

The length z_0 is in principle the height at which the wind speed is zero. For homogeneous terrain, the larger the roughness elements of the landscape then the larger is the length z_0. When the terrain is homogeneous, the roughness length can be determined using observed wind profiles during near neutral conditions by extrapolating a logarithmic profile to zero wind speed.

As is more often the case, the landscape contains occasional obstructions or large perturbations. For these situations, the effective roughness length must be determined for use in the surface layer similarity relationships. The effective roughness length is best determined using σ_U/US data or gustiness.[31,32] The relationship between σ_U/US and z_0 is,

$$\sigma_U/US = 1/\ln(Z/z_0) \qquad (6.4.2)$$

where Z is the measurement height of σ_U and US. The estimation procedure involves only cases when the 10m scalar averaged wind speed is greater than 5 m/s. The sampling duration for σ_U and US should be at least 3 minutes and may be as long as 60 minutes. The procedure has been applied successfully using 15 minute data.[33]

Turbulence data at several levels may be available for use in the analysis. To select the levels for use in the analysis, an initial estimate of the effective roughness length must be made. A visual inspection of the landscape is sufficient for this initial estimate using

Table 6-1.[32] Only data collected above $20z_0$ and below $100z_0$ are selected for use in the analysis. For sites with very low roughness, these criteria are slightly modified. The lower bound of measurement height should never be less than 1.0m. The upper bound should never be less than 10m.

Estimates of z_0 should be made for each case using (6.4.2). The results should be sorted by wind sector. As many wind sectors as needed to distinguish between major variations should be selected. No sector should be less than 30 degrees in width. For each sector, the median z_0 value should be computed, and the results inspected to determine whether the variation between sectors is significant. For sectors with no significant variation in the median z_0 values, an average of the median values should be computed.

The resulting estimate of z_0 is accurate to one significant figure, e.g., a computed z_0 value of 0.34m is rounded to 0.3m for use in succeeding diffusion analyses.

Table 6-1. Terrain Classification in Terms of Effective Surface Roughness Length, z_0.[32]

Short 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	0.5
Regular large obstacle coverage (suburb, forest)	(0.5-1.0)

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

6.4.3 Surface Friction Velocity

The characteristic velocity based on surface stress is called the friction velocity, u*. It is defined as,

$$u^* = (\tau_0/\rho_0)^{1/2} \qquad (6.4.3)$$

where

$\tau_0 = -\rho_0\overline{u'w'}$

ρ_0 = representative boundary layer air density

$\overline{u'w'}$ = average covariance of along (u') and vertical (w') wind fluctuations.

In surface layer similarity theory, the friction velocity, accounts for the effects of the large-scale pressure field and the surface roughness. Also, u* is representative of the turbulent wind fluctuations in the lower layer of the boundary layer. Hence, u* is useful as a velocity scale near the surface.

For neutral stability conditions, u* can be estimated from the wind speed profile. However, this is only possible in ideal circumstances. In practice, u* is estimated using empirical similarity relationships that describe the wind and temperature profiles in the surface layer.

A variety of methods are available for estimating u*. The choice of method is dependent upon the type of meteorological data available. In all the estimation methods, the scalar mean wind speed is used. Only wind speed and temperature data collected within the height range from $20z_0$ to $100z_0$ are used. For sites with very low roughness, these criteria are slightly modified. The lower bound of measurement height should never be less than 1.0m. The upper bound should never be less than 10m. To obtain

1-hour averages, the sampling duration 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.

When temperature and wind speed are available at three or more heights, use of the procedure presented by Nieuwstadt[34] is recommended. Wind speed at one level and direct measurements of temperature difference in the vertical may be available. For these cases the procedures outlined by Irwin and Binkowski should be used.[35] When only the routine weather observations are available, u* should be estimated with the procedure outlined in the appendix to the article by Holtslag.[36] The latter two procedures are incorporated into the meteorological processor, MPDA-1.[28]

Given the uncertainty of the empirical constants used in the estimation methods, there is at least a 20% uncertainty associated with the u* estimate. This means that at best u* estimates have two significant figures accuracy. Often, especially for the cases using the routine weather observations, the estimate has only one significant figure accuracy.

6.4.4 Pasquill Stability Categories

For existing regulatory models stability conditions are assessed by means of the Pasquill stability categories. The original category definitions, Table 6-2, are in terms of insolation amount, cloud amount and 10m wind speed.[37] The categories are simplified estimates of the flux Richardson number (see Section 6.4.5.1). Category A is very unstable conditions and category F is moderately stable conditions. Strong insolation corresponds to sunny midday in midsummer in England, slight insolation 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.

Table 6-2. Original Definitions of Pasquill Stability Categories.[37]

Surface wind speed (m/s)	---Insolation---			----Night----	
	Strong	Moderate	Slight	Thinly overcast or $\geq 4/8$ low cloud	$\leq 3/8$ cloud
<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

The Guideline on Air Quality Models (Revised)[4] recommends that the Pasquill stability category be determined from one of the following schemes, in order of preference:

(1) Turner's 1964 method[38] using site-specific data which include cloud cover, ceiling height and surface (~10m) wind speed;

(2) σ_E from site-specific measurements modified by wind speed (σ_E may be determined from elevation angle measurements or may be estimated from measurements of σ_W according to the transform: $\sigma_E = \sigma_W/UV$ (see Section 6.4.1));

(3) σ_A from site-specific measurements modified by wind speed; or

(4) Turner's 1964 method using site-specific wind speed with cloud cover and ceiling height from a nearby NWS site.

These methods are described in more detail in the following sections. Alternative methods for stability category determination must be evaluated in consultation with the Regional Office prior to their use.

6.4.4.1 Turner's 1964 method

Turner[38] presented a method for determining Pasquill 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 6-3 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 determined from the following procedure:

1. If the total cloud 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 ratiation 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 6-4.

   (b) If total cloud cover $\leq$5/10, use the net radiation index in Table 6-3 corresponding to the isolation class number.

(c) If cloud cover >5/10, modify the insolation class number by the following six steps.

(1) 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 wit 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 6-3 corresponding to the modified insolation class number.

Solar altitude can be determined from the Smithsonian Meteorological Tables.[39] For EPA regulatory modeling applications, stability classes 6 and 7 (F and G) are combined and considered Class 6.

Table 6-3. Stability Class as a Function of Net Radiation and Wind Speed.

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

Table 6-4. Insolation as a Function of Solar Altitude.

Solar Altitude (a)	Insolation	Insolation Class Number
60°<a	strong	4
35°<a<60°	moderate	3
15°<a≤35°	slight	2
a≤15°	weak	1

6.4.4.2 Vertical turbulence (σ_E) and wind speed method

The following discussion describes a method for estimating Pasquill stability categories in terms of the standard deviation of the vertical wind direction fluctuations, σ_E, and the scalar mean wind speed, US. The reader should note that the method and parameters specified in this subsection are identical with those in the Guideline on Air Quality Models (Revised).[4] However, several refinements are added that provide for wider applicability and for less ambiguous distinctions between stability classes.

The criteria in Table 6-5a and Table 6-5b are for data collected at 10m and the roughness length is 15 cm. For use in Table 6-5b, nighttime is the period from one hour before sunset to one hour after sunrise. 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 1.0m; the upper bound should never be less than 10m. 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 6-5a. Vertical Wind Direction Turbulence Criteria for Initial Estimate of Pasquill Stability Category. Use with Table 6-5b.

Initial estimate of Pasquill stability category	Standard deviation of vertical wind direction fluctuations, σ_E, in degrees
A	$11.5 \le \sigma_E$
B	$10.0 \le \sigma_E < 11.5$
C	$7.8 \le \sigma_E < 10.0$
D	$5.0 \le \sigma_E < 7.8$
E	$2.4 \le \sigma_E < 5.0$
F	$\sigma_E < 2.4$

Table 6-5b. Wind Speed Adjustments for Determining Final Estimate of Pasquill Stability Category from σ_E. Use with Table 6-5a.

	Initial estimated category	10m scalar wind speed (US) (m/s)	Final estimate of stability category
Daytime			
	A	US <3	A
		$3 \le$ US <4	B
		$4 \le$ US <6	C
		$6 \le$ US	D
	B	US <4	B
		$4 \le$ US <6	C
		$6 \le$ US	D
	C	US <6	C
		$6 \le$ US	D
	D,E or F	ANY	D
Nighttime			
	A	ANY	D
	B	ANY	D
	C	ANY	D
	D	ANY	D
	E	US <5	E
		$5 \le$ US	D
	F	US <3	F
		$3 \le$ US <5	E
		$5 \le$ US	D

If the site roughness length is other than 15 cm, the category boundaries listed in Table 6-5a may need adjustment. As an initial adjustment, multiply the values listed by,

$$(z_0/15)^{0.2},$$

where z_0 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_0 is greater than 15 cm. It is yet problematical whether the adjustment is as useful for cases when z_0 is less than 15 cm.

If the measurement height is other than 10m, the category boundaries listed in Table 6-5a will need adjustment. As an initial adjustment, multiply the lower bound values listed by,

$$(Z/10)^{pe},$$

where Z is the measurement height in meters. The exponent pe varies as a function of stability category as,

To determine new lower bound for category	Value of pe
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 midafternoon 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 may tailor the turbulence criteria to the particular site characteristics, but should be made only in consultation with the reviewing agency.

6.4.4.3 Lateral turbulence (σ_A) and wind speed method

The following discussion describes a method for estimating Pasquill stability categories in terms of the standard deviation of the horizontal wind direction fluctuations, σ_A, and the scalar mean wind speed, US. *The reader should note that the method and parameters* specified in this subsection are identical with those in the Guideline on Air Quality Models (Revised).[4] However, several refinements are added that provide for wider applicability and for less ambiguous distinctions between stability classes.

The criteria in Table 6-6a and Table 6-6b are for data collected at 10m and the roughness length is 15 cm. For use in Table 6-6b, nighttime is the period from one hour before sunset to one hour after sunrise. 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 1.0m. The upper bound should never be less than 10m. 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 6-6a. Lateral Wind Direction Turbulence Criteria for Initial Estimate of Pasquill Stability Category. Use with Table 6-6b.

Initial estimate of Pasquill stability category	Standard deviation of horizontal wind direction fluctuations, σ_A, in degrees
A	$22.5 \le \sigma_A$
B	$17.5 \le \sigma_A < 22.5$
C	$12.5 \le \sigma_A < 17.5$
D	$7.5 \le \sigma_A < 12.5$
E	$3.8 \le \sigma_A < 7.5$
F	$\sigma_A < 3.8$

Table 6-6b. Wind Speed Adjustments for Determining Final Estimate of Pasquill Stability Category from σ_A. Use with Table 6-6a.

	Initial estimated category	10m scalar wind speed (US) (m/s)	Final estimate of stability category
Daytime	A	US < 3	A
		3 ≤ US < 4	B
		4 ≤ US < 6	C
		6 ≤ US	D
	B	US < 4	B
		4 ≤ US < 6	C
		6 ≤ US	D
	C	US < 6	C
		6 ≤ US	D
	D,E or F	ANY	D
Nighttime	A	US < 2.9	F
		2.9 ≤ US < 3.6	E
		3.6 ≤ US	D
	B	US < 2.4	F
		2.4 ≤ US < 3.0	E
		3.0 ≤ US	D
	C	US < 2.4	E
		2.4 ≤ US	D
	D	ANY	D
	E	US < 5.0	E
		5.0 ≤ US	D
	F	US < 3.0	F
		3.0 ≤ US < 5.0	E
		5.0 ≤ US	D

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

$$(z_0/15)^{0.2},$$

where z_0 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_0 is greater than 15 cm. It is yet problematical whether the adjustment is as useful for cases when z_0 is less than 15 cm.

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

$$(Z/10)^{pa},$$

where Z is the measurement height in meters. The exponent pa varies as a function of stability category as,

To determine new lower bound for category	Value of pa
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 midafternoon 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 may tailor the turbulence criteria to the particular site characteristics, but should be made only in consultation with the reviewing agency.

6.4.4.4 Accuracy of stability category estimates

Results are not available comparing the performance of the methods outlined above in this section. There are comparison results for similar methods. From these studies, it is concluded that the methods will estimate the same stability category about 50% of the time. They will estimate within one category of each other about 90% of the time. Adjustment of the turbulence criteria resulting from spot checks is necessary to achieve this performance.

6.4.5 Other Stability Measures

6.4.5.1 Flux Richardson number

Buoyancy forces may act to enhance or suppress turbulent wind fluctuation motions. A very useful measure in this regard is the flux Richardson number, R_f,

$$R_f = -\frac{\text{Production of turbulent thermal kinetic energy}}{\text{Production of turbulent mechanical kinetic energy}} .$$

The denominator is always positive near the surface. R_f is negative when buoyant forces tend to enhance turbulent motions in the vertical. It is positive when buoyant forces tend to suppress turbulent motions in the vertical. Stable conditions exist when R_f is positive. When R_f is near zero, stability conditions are neutral. During such times, the wind speed profile often varies linearly with the logarithm of height. When R_f is negative, stability conditions are unstable.

6.4.5.2 Monin-Obukhov length

A more easily estimated stability measure, related to R_f, is the Monin-Obukhov length, L,

$$R_f = Z/L.$$

A variety of methods are available for estimating L. The choice of method is dependent upon the type of meteorological data available. In all the estimation methods, use the scalar mean wind speed. Only wind speed and temperature data collected within the height range from $20z_0$ to $100z_0$ are used. For sites with very low roughness, these criteria are slightly modified. The lower bound of measurement height should never be less than 1.0m. The upper bound should never be less than 10m. To obtain 1-hour averages, the sampling duration 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.

When temperature and wind speed are available at three or more heights, use of the procedure presented by Nieuwstadt[34] is recommended. Wind speed at one level and direct measurements of temperature difference in the vertical may be available. For these cases the procedures outlined by Irwin and Binkowski should be used[35]. When only the routine weather observations are available, L should be estimated with the procedure outlined in the appendix to the article by Holtslag[36]. The latter two procedures are incorporated into the meteorological processor, MPDA-1.[28]

The uncertainty of the empirical constants used in the estimation methods means that at best L estimates have two significant figures accuracy. Often, especially for the cases using the routine weather observations, the estimate has only one significant figure accuracy.

6.5 Model Inputs

The majority of point source models recommended in EPA's Guideline on Air Quality Models (Revised)[4] require that hourly meteorological data be input in a format that has been standardized by EPA's meteorological preprocessor program.[12] EPA desires to maintain this consistency and extend it to on-site meteorological data sets. EPA is developing a meteorological processor for regulatory applications (MPRA) that will provide this consistency when available.

6.5.1 Formats

As noted above, the input data format for EPA short-term regulatory models has been standardized by the meteorological preprocessor, RAMMET, as described in Reference 12. A consistent format for model input should be used when processing on-site meteorological data. Since on-site wind direction data are reported to the nearest degree, the actual observed winds should be repeated in the field reserved for the randomized flow vector generated for National Weather Service (NWS) data. The input format for the EPA long-term models should be of the stability wind rose (STAR) variety generated for NWS stations by the National Climatic Data Center. Individual model user's guides should be referred to for additional details on input data formats.

6.5.2 Treatment of Calms

EPA's policy is to disregard calms until such time as an appropriate analytical approach is available. The recommended EPA models contain a routine that eliminates the effect of the calms by nullifying concentrations during calm hours and recalculating short-term and annual average concentrations. Certain models lacking this built-in feature can have their output processed by EPA's CALMPRO program[40] to achieve the same effect. Because the adjustments to the concentrations for calms are made by either the models or by postprocessor, actual measured on-site wind speeds should always be input to the preprocessor. These actual wind speeds should then be adjusted as appropriate under the current EPA guidance[4] by the preprocessor.

Measured on-site wind speeds of less than 1.0 m/s, but above the instrument threshold, should be set equal to 1.0 m/s by the preprocessor when used as input to Gaussian models. Wind speeds below the starting threshold of the anemometer or vane, whichever is greater, should be considered calm. Calms are identified in the preprocessed data file by a wind speed of 1.0 m/s and a wind direction equal to the previous hour.

6.5.3 Treatment of Missing Data

Missing data refers to those hours for which no data are available from the primary on-site source for the variable in question.

In order for the regulatory models to function properly, there must be a data value in each input field. When missing values arise, they should be handled in one of the ways listed below, in the following order of preference.

(1) If there are other on-site data, such as measurements at another height, they may be used when the primary data are missing. If the height differences are significant, corrections based on established vertical profiles should be made. Site-specific vertical profiles based on historical on-site data may also be appropriate to use if their determination is approved by the reviewing authority (see Section 6.1.3). If there is question as to the representativeness of the other on-site data, they should not be used.

(2) If there are only one or two missing hours, then linear interpolation of missing data may be acceptable, however, caution should be used when the missing hour(s) occur(s) during day/night transition periods.

(3) If representative off-site data exist, they may be used. In many cases this approach may be acceptable for cloud cover, ceiling height, mixing height and temperature. This approach will rarely be acceptable for wind speed and direction. The representativeness of off-site data should be discussed and agreed upon in advance with the reviewing authority (see Section 6.6).

(4) Failing any of the above, the data field should be coded as a field of nines. This value will act as a missing data flag in any further use of the data set.

At the present time, the short term regulatory models contain no mechanism for handling missing data in the sequential input file.

Therefore, in order to run these models a complete data set, including substitutions, is required. Substitutions for missing data should only be made in order to complete the data set for modeling applications, and should not be used to attain the 90% data retrieval recommended in Section 5.0.

6.6 Use of Off-Site Data

6.6.1 Representativeness of Meteorological Data

Evaluations of the atmospheric dispersion characteristics of the site of a pollutant source, make it necessary to determine if available meteorological data can be used to adequately characterize the atmospheric dispersion conditions.

Such determinations are required when the available meteorological data are acquired at a location other than that of the proposed source. In some instances, even though meteorological data are acquired at the location of the pollutant source, they still may not correctly characterize the important atmospheric dispersion conditions.

Considerations of representativeness are always made with the meteorological data sets used in atmospheric dispersion modeling whether the data base is "on-site" or "off-site." These considerations call for the judgment of a meteorologist or an equivalent professional with expertise in atmospheric dispersion modeling.

Representativeness has been defined in the Workshop on the Representativeness of Meteorological Observations[41] 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." Any judgments of the representativeness of meteorological data should necessarily factor in considerations of spatial and temporal dependence.

6.6.1.1 Spatial dependence

The location where the data base was acquired should be compared to the source location for similarity of terrain features. For example, in complex terrain, the following considerations should be addressed:

1. Aspect ratio of terrain, i.e., ratio of:
   a. Height of valley walls to width of valley;
   b. Height of ridge to length of ridge; and
   c. Height of isolated hill to width of hill at base.
2. Slope of terrain
3. Ratio of terrain height to stack/plume height.
4. Distance of source from terrain, i.e. how close to valley wall, ridge, isolated hill.
5. Correlation of terrain feature to prevailing meteorological conditions.

Likewise, if the source is to be located on a plateau or plain, the source of meteorological data should be from a similar plateau or plain.

Judgments of representativeness should be made only when sites are climatologically similar. Sites in nearby but different air sheds often exhibit different weather patterns. For instance, meteorological data acquired along a shoreline are not normally representative of inland sites and vice versa.

Meteorological data collected need to be examined to determine if drainage, transition, and synoptic flow patterns are characteristics of the source, especially those critical to the regulatory application. Consideration of orientation, temperature, and ground cover should be included in the review.

An important aspect of space dependence is elevation above the ground. Where practical, meteorological data should be acquired at the release elevation, as well as above or below, depending on the buoyancy of the source's emissions.

6.6.1.2 Temporal dependence

To be representative, a meteorological data base must be of sufficient duration to define the range of sequential atmospheric conditions anticipated at a site. As a minimum, one year of on-site meteorological data covering the four seasons is necessary to prescribe this time series. Multiple years of data are used to describe variations in annual, and short term impacts. In general, the climatic period of five years is adequate to represent these yearly variations. The length of the required data period relates to the standard being addressed. In general, the longer the time period of the ambient air quality standard, the longer the period of meteorological data required to demonstrate compliance with that standard.

6.6.1.3 Further considerations

It must also be recognized that consideration of alternative data sets extends beyond space and time representation. The data from the onset must be compatible with the impact analysis requirements as set forth in the source's modeling protocol. If a meteorological data set were acquired in an incompatible form, it may be considered inadequate and, therefore, "not representative." Also, consideration must be given to the response characteristics of the instruments and their ability to correctly describe the atmospheric dispersion processes. If these response characteristics restrict the instrument from sensing the most critical atmospheric processes (those resulting in the highest impacts), they may not be representative from an atmospheric dispersion standpoint.

It may be necessary to recognize the non-homogeneity of meteorological variables in the air mass in which pollutants disperse. This non-homogeneity may be essential in correctly describing the dispersion phenomena. Therefore, measurements of meteorological variables at multiple locations and elevations may be required to correctly represent these meteorological fields. Such measurements are generally required in complex terrain or near large land-water body interfaces.

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.

Other factors affecting representativeness include change in surface roughness, topography and atmospheric stability.

Currently there are no established analytical or statistical techniques to determine representativeness of meteorological data. As implied above, any criteria would be variable-specific and involve a judgment based on case-by-case considerations. Even if such criteria could be established, they would require the acquisition of some on-site data. The establishment and maintenance of such an on-site data collection program generally fulfills the requirement for "representative" data.

6.6.2 Alternative Meteorological Data Sources

It is necessary in the consideration of most air pollution problems to obtain information on site-specific atmospheric dispersion. Frequently, an on-site measurement program must be initiated. As discussed in Section 6.5.3, representative off-site data may be used to substitute for missing periods of on-site data. There are also situations where current or past meteorological records from a National Weather Service station may suffice. The following outline provides a brief insight into the types of observations taken at Weather Stations and some of the summaries compiled from this data.

6.6.2.1 National Weather Service (NWS)

(a) First Order Stations

There are about 200 National Weather Service (NWS) stations where 24 hourly observations are taken daily. Among the measurements taken are: dry bulb temperature and wet bulb temperature (from which dew point temperature and relative humidity are calculated), pressure, wind direction and speed, cloud cover and visibility. The National Climatic Data Center (NCDC) in Asheville, North Carolina, maintains records of these observations.

(b) Second Order Stations

These stations usually take hourly observations similar to the first order stations above, but not throughout the entire day.

6.6.2.2 Military observations

Many military installations, especially Air Force Bases, take hourly observations. These are transmitted on military teletype circuits and therefore are not usually available for general use. No routine publication of these data is done. Records of observations are sent to NCDC where special summaries can be made.

6.6.2.3 Supplementary Airways Reporting Stations

These stations are at smaller airports. The observations are not at regular intervals, usually being taken according to airline schedules at the airport. These observations are not published and are not usually digitized. Original records are sent to NCDC, however.

6.6.2.4 Upper air

There are between 60 and 70 stations in the contiguous United States where upper air observations are taken twice daily (at 0000 GMT and 1200 GMT) by radiosonde balloon and radio direction-finding equipment. The measurements made are temperature, pressure, and relative humidity with height and wind speed and direction. These data are obtained primarily for knowledge of the large scale meteorological pattern and have relatively little refinement in the lower 500 to 1000 meters of the atmosphere. These observations are transmitted by teletype and original records sent to NCDC where these data are published. These data form the basis for most determinations of mixing height input to regulatory air quality models.

6.6.2.5 Evaluation of NWS and military data sources

If these NWS and military meteorological data sources are to be used in making atmospheric dispersion estimates of a source, a judgment as to the representativeness of these data sources should be made using the considerations provided in Section 6.6.1 above.

In addition, it must be recognized that these data sources have the following limitations:

(a) Human error

The observational data are a result of human interpretation and as such are then subject to individual bias and variation in reported data. Such observational bias is sometimes apparent upon review of the data. For instance, some observers will report wind directions to the nearest 20 degrees, resulting in a higher frequency of occurrence of even numbered wind directions. This is apparent from a casual observation of the wind rose constructed on such a biased data set. It is important that all relevant NWS meteorological observational data be reviewed for human bias.

(b) Accuracy of the wind direction observation

Wind directions are only reported to the nearest 10 degrees, with no attempt to electronically average the data. Dispersion modeling estimates for short term impacts have traditionally relied upon directions specified to the nearest degree. In order to achieve that level of specificity and consistency, EPA has generated a random number string to be applied to the data set.

(c) Time period of observation

While on-site meteorological data are generally of a continuous nature, NWS and military observations are constrained to a short time period preceding the hour. Gradual shifts in the data over that time period are generally unreported. Other significant shifts in observations, although observed and reported are not handled by the meteorological data preprocessor. These shortcomings are known to be inherent in such data yet, historically, these observations have provided acceptable data for regulatory applications.

6.6.2.6 Meteorological data from private networks

As with NWS and military data sources, meteorological data acquired from private monitoring networks may be used in making atmospheric dispersion estimates of a source if judged to be representative by the criteria provided in Section 6.6.1 above.

Data from such sources may not be accompanied by the problems associated with NWS and military data as noted above. However, such meteorological data sets are not generally subject to the same level of public dissemination and review. Therefore, any use of such data sets should be accompanied by a review of the quality assurance plans for these data acquisition systems. Such meteorological data should be collected in accordance with the guidance on quality assurance and maintenance contained in Section 8.0 of this document.

6.7 Recommendations

It is recommended that for hourly mean wind statistics in straight-line Gaussian dispersion models, scalar wind speed and scalar wind direction processing be used. For microprocessor-based digital systems, the unit vector mean wind direction is also acceptable. The standard deviation of the wind direction fluctuations should be calculated about the scalar or unit vector mean direction, or may be estimated using the techniques of Mardia[24] or Yamartino[26]. These hourly values may be obtained by averaging samples over an entire hour or by averaging a group of shorter period averages. If shorter period averages are used, it is recommended that wind statistics be computed over intervals of 15 minutes, and that at least two valid 15-minute periods be averaged to represent the hour. A minimum of

360 data samples should be used to calculate the standard deviation and at least 60 samples should be used to calculate the mean, regardless of the averaging period. Thus, to calculate the standard deviation for a 15-minute sampling duration, the data should be sampled at least once every 2.5 seconds, and if the data are only averaged every hour, then the data should be sampled at least once every ten seconds. If the single-pass processor described by Equations 6.1.4 and 6.1.5 in Section 6.1.2 is used for wind direction, it is recommended that the data be sampled at least once per second, to assure that the difference between consecutive values is less than 180°.

The hourly vertical temperature gradient may be determined by averaging samples over the entire hour or by averaging a group of shorter period averages. If shorter period averages are used, it is recommended that four 15-minute averages be used with at least 60 samples for each 15-minute period. For other primary variables, including temperature, dew point, pressure and radiation, four 15-minute averages of digital data are recommended, but one-hour point or one-hour average analog values may be acceptable. Precipitation data should be processed to obtain a total for every hour.

It is recommended that effective roughness length be determined from equation 6.4.2

The atmospheric stability category should be determined from one of the following schemes, following the order of preference given in the Guideline on Air Quality Models (Revised):[4]

(1) Turner's 1964 method[38] using site-specific data which include cloud cover, ceiling height and surface (~10m) wind speeds;

(2) σ_E from site-specific measurements modified by wind speed (σ_E may be determined from elevation angle measurements or may be estimated from measurements of σ_W according to the transform: $\sigma_E = \sigma_W/US$ (see Section 6.4.1));

(3) σ_A from site-specific measurements modified by wind speed; or

(4) Turner's 1964 method using site-specific wind speed with cloud cover and ceiling height from a nearby NWS site.

Alternative methods for determining stability category must be evaluated in consultation with the Regional Office prior to their use.

On-site meteorological data should be processed to provide input data in a format consistent with the particular models being used. The input format for EPA short-term regulatory models is defined in Reference 12. The format for EPA long-term models is the STAR format utilized by the National Climatic Data Center. The actual wind speeds should be coded on the original input data set. Wind speeds less than 1.0 m/s but above the instrument threshold should be set equal to 1.0 m/s by the preprocessor when used as input to Gaussian models. Wind speeds below the instrument threshold of the cup or vane, whichever is greater, should be considered calm, and are identified in the preprocessed data file by a wind speed of 1.0 m/s and a wind direction equal to the previous hour.

If data are missing from the primary source, they should be handled as follows, in order of preference: (1) substitution of other representative on-site data; (2) linear interpolation of one or two missing hours; (3) substitution of representative off-site data; or (4) coding as a field of nines, according to the discussions in Section 6.5.3 and 6.6. However, in order to run existing short-term regulatory models, a complete data set, including substitutions, is required.

If the data processing recommendations in this section cannot be achieved, then alternative approaches should be developed in conjunction with the Regional Office.

7.0 DATA REPORTING AND ARCHIVING

Because of the different data requirements for different types of analyses, there is no fixed format that applies to all data sets. However, a generalization can be made. All on-site meteorological data should be collated in chronological order and tabulated according to the observation time. Observation time should be defined as the time at the beginning of the averaging period, e.g., 0100 refers to the period from 0100 to 0200. Note that NWS data is based on a somewhat different recording scheme and cannot be interpreted in the same manner. If an EPA regulatory decision is involved, the on-site data must be furnished to the reviewing agency upon request.

7.1 Reporting Formats

When data are requested by the reviewing agency, two types of reports will generally be required. The first will be a written summary report which should include a discussion of the overall monitoring program followed by details on data sources, data quality, completeness, data handling procedures and computational methods. The second report will include the actual data. Different forms of actual data reporting are discussed briefly below.

7.1.1 Preprocessed Data

In most cases, the reviewing agency will request a copy of the preprocessor output in tape and hardcopy form.

7.1.2 SAROAD/AIRS

In some cases, the reviewing agency will require that validated measured data be reported to EPA's ambient monitoring data base system (SAROAD/AIRS) on a quarterly basis. In these instances, all variables that have a SAROAD/AIRS parameter code should be submitted in SAROAD/AIRS format on a quarterly basis. In some cases, both preprocessor output and SAROAD/AIRS format data may be required.

7.2 Archiving

While there are currently no EPA regulatory requirements for meteorological data archiving, it is considered prudent practice for collectors of such data to establish an archiving program. When the data are being collected for use in a regulatory setting, they must be made available to the reviewing agency upon request. Thus, until a particular regulatory action is complete, all data must be available. Since a particular data set may have applicability in more than one regulatory action, or since litigation may follow a regulatory action, the need for the raw data set may extend well beyond its original application. EPA suggests the following considerations in designing an archiving program.

7.2.1 Raw Data

The raw data records are the most basic data elements and should be given the highest priority in archiving. The raw data may include variables that, although not currently used by recommended models, might be used in future models. Therefore, comprehensive archiving is recommended. Hourly averaged data should be stored in machine-readable form, e.g., magnetic tape, for convenience and easy access. However, magnetic tapes need to be copied periodically to insure integrity, and care should be taken to select a format for encoding the data that will be as compatible as possible with other computer systems. Where data were originally reduced from strip chart records, the charts should also be archived.

7.2.2 Preprocessed Data

Since, in theory, all preprocessed data can be recreated from the raw data, the preprocessor data should be given a lower priority. However, the ready-to-use nature of the preprocessor output and the cost of preprocessing raw data argue strongly for archiving the preprocessed data as well.

7.2.3 Retention Time

Experience shows that good data sets have long, useful lives and thus should be archived as long as possible. When evaluating whether an old data set remains useful, primary consideration should be given to a comparison of the actual collection program with the most current guidance. As long as the instrumentation, siting, quality assurance and completeness criteria are still satisfied, it is recommended that the data be retained indefinitely in machine-readable form. 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 beforehand to contact other modelers who may wish to receive the data.

7.3 Recommendations

In general, the data reporting and archiving requirements will be worked out in consultation with the reviewing agency. An agency may request meteorological data in either a preprocessed form, or in the SAROAD/AIRS data base format, or both. All meteorological data must be available to the reviewing agency until a regulatory action is completed. However, the need for a data set may extend beyond its original application due to litigation, or due to its applicability to another regulatory action. Therefore, it is recommended that data be retained indefinitely, provided that the guidance criteria for on-site meteorological monitoring are still satisfied. It is recommended that the observation time reported refer to the time at the beginning of the averaging period.

8.0 QUALITY ASSURANCE AND MAINTENANCE

The purpose of quality assurance and maintenance is the generation of a representative amount (90% of hourly values for a year, Section 5.3.2) of valid data (Sections 5.1 and 8.6). Maintenance may be considered the physical activity necessary to keep the measurement system operating as it should. Quality assurance is the management effort to achieve the goal of valid data through plans of action and documentation of compliance with the plans.

Quality assurance (QA) will be most effective when following a QA Plan which has been signed-off by appropriate project or organizational authority. The QA Plan should contain the following information (paraphrased and particularized to meteorology from Lockhart[42]):

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 for the person providing the quality assurance (QA) function to be independent of the organization responsible for the collection of the data and the maintenance of the measurement systems. Ideally, the QA auditor works for a separate 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.

The subsections will be specific to the variable to be measured. Wind speed will refer to those common mechanical anemometers (cups and vane-oriented propellers) which use the pressure force of the air passing the aerodynamic shape of the anemometer to turn a shaft. Except for Doppler SODARS (see Section 9.0), the more complicated indirect or remote measuring systems, such as sonic anemometers, hot wire or hot film anemometers, laser anemometers and the like, are not commonly used for routine monitoring and are beyond the scope of this guide.

Wind direction will refer to common wind vanes which provide a relative direction with respect to the orientation of the direction sensor. There are three parts of the direction measurement which must be considered in quality assurance. These are (1) the relative accuracy of the vane performance in converting position to output, (2) the orientation accuracy in aligning the sensor to TRUE NORTH and vertical, with respect to a level plane, and (3) the dynamics of the vane and conditioning circuit response to turbulence for calculation of sigma theta.

Temperature and temperature difference require QA focused on the application of the data. Dew point temperature, precipitation, atmospheric pressure and radiation are also addressed.

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

The performance specification for an anemometer might read:

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 (standard sea-level density)

(1) as determined by wind tunnel tests conducted on production samples in accordance with ASTM D-22.11 test methods.[21]

(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 which represents the threshold speed, above which the anemometer will be out of specification. The latter value is a flag requiring the action of bearing or sensor replacement.

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

The performance specification for the wind vane might read:

Range	001 to 360 degrees or 001 to 540 degrees
Threshold (1)	≤0.5 m/s
Accuracy (error)(1)	≤3 degrees relative to the sensor mount or index (≤5 degrees absolute error for installed system)
Delay Distance (1)	≤5 m at 1.2 kg/m^3 (standard sea-level density)
Damping Ratio (1)	≥0.4 at 1.2 kg/m^3 or
Overshoot (1)	≤25% at 1.2 kg/m^3

(1) as determined by wind tunnel tests conducted on production samples in accordance with ASTM D-22.11 test methods.

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 which represents the threshold speed, above which the vane will be out of specification. The latter value is a flag requiring the action of bearing or sensor replacement.

The range of 001 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 automatic 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 (001 to 360 degree) system without excessive errors for either average direction or sigma theta.

If the wind direction samples are to be used for the calculation of sigma theta, 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 sigma theta 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 degrees C.
Accuracy (error)	$\leq$ 0.5 degree C.

A temperature difference specification might read:

Range	-5 to +15 degrees C.
Relative accuracy (error)	$\leq$ 0.1 degrees 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 degrees 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 degree 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 gage. AC power must be available to the precipitation measurement site. For remote sites where AC power is not available, propane-heated gages 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 gage can affect the amount of catch. For example, Weiss[43] reports that at a wind speed of 5 mph, the collection efficiency of an unshielded gage decreased by 25%, and at 10 mph, the efficiency of the gage decreased by 40%. Therefore, it is recommended that all precipitation gages be installed with an Alter-type wind screen, except in locations where frozen precipitation does not occur.

Exposure is very important for precipitation gages; 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 gage from the data acquisition system.

If a weighing gage 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 Acceptance Testing

It is common for acceptance tests to be just checking the shipment part numbers against the packing slip. Lacking more detailed instructions, it is all a receiving department can do. Such a test does not provide any technical information.

8.2.1 Wind Speed

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

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. This could be verified.

If sigma theta 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 sigma theta 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 1 degree 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 gage is straightforward. With the sensor connected to the system, check its response to water (or equivalent weight for weighing gages) 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

It is not possible to generalize a routine calibration. One system design might require "routine calibrations" quarterly while another might require them daily. This section will address what the calibration should be and how the required period might be determined. For this section, all variables will be considered under each category.

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 gages 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 3.0m, it may increase to 3.5m in Denver and 4.3m 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 sigma theta.

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 degrees 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 degrees C, 15 to 25 degrees C, and 30 to 40 degrees C are recommended. A maximum difference among the three temperatures (i.e., 0, 20, and 40 degrees 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:

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

B. Name of calibration person or team members

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

D. Where the data sheet or sheets can be found on site

E. 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

Frequency of calibration may be determined by an iterative process; the minimum period may be fixed by regulation. Whenever a calibration of the type described in 8.3.1.2 is conducted, monitored data are lost. The first field calibration should be just after installation is completed. The second might be a week later. If problems are found and corrected, the one week period should be repeated. When no problems are found, the next calibration might be a month later. If no problems are found at one month, the next calibration might be three months later. If the next calibration is another three months later and shows no problems, try six months. The system should be calibrated at least every six months.

It must be clearly understood that the risk of the loss of large amounts of data increases when long periods of time are allowed to pass without any attention paid to the data or the instrument. The method of establishing the frequency of calibrations presumes the existence of operational checks and preventive maintenance as described below. The most important function to avoid loss of large amounts of data is the routine (daily or at least weekly) quality control (QC) inspection of the data by an experienced meteorologist. The data themselves will usually expose failures of the measurement system. The lack of problems reported from progressively less frequent calibration and the experience gained from weekly assessment of data validity is the most cost effective method for archiving the most valid data. A carefully followed program of preventive maintenance will lower the risk of large blocks of invalid data.

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 system audit (see Ref. 44) is intended to provide an independent assessment of the QA Plan, how it is being implemented, and how the evidence of the operator's actions is kept. Given the joint goal of the auditor and the operator to achieve valid data with defendable documentation, the audit becomes a training tool. Whichever is the most experienced will teach the other for the good of the joint goal.

When the period of time between calibrations or performance audits is three months or longer, it is critical to examine the methods by which the experienced quality control meteorologist determines the validity of the data on a routine schedule. It is also important to assure the proper documentation of the data inspection process where changes or selective deletions are allowed.

The performance audit is a direct challenge to the performance of the measurement system. The recommended methods described in 8.3.1.2 are the same as would be used in a performance audit for the reason mentioned in Section 8.0.

The use of a collocated transfer standard is an additional challenge to be considered. This is accomplished by locating a like instrument as close as practical to the instrument being audited to serve as a standard for comparison of the transfer function. If a good exposure is possible for a collocated instrument, such a test can be considered a substitute for a wind tunnel test of the transfer function. The wind tunnel will always be superior for controlled testing in laminar flow. The data taken in Boulder, Colorado and partially reported in Kaimal et al.[45] suggest a collocated instrument can provide an opportunity to assess the absolute accuracy of a monitoring system within the accuracy specifications listed in Section 8.1. If a suitable data sample size is achieved over a reasonable range of wind speeds (usually found in a few diurnal cycles), the average difference can be considered the accuracy error and the root-mean-square of the difference can qualify the test period and relative siting as acceptable or not. An experienced assessment of exposure is critical to the proper use of this method.

Somewhere between the system audit and the performance audit is found the independent technical appraisal of such things as the suitability of the deployment of sensors with respect to the intended data application (sensor siting, Section 3.0), the sample summarization method (Section 6.1.2), and model suitability (Section 6.5). The value of this type of appraisal is proportional to the qualifications of the auditor, but the fact that these questions are addressed at all will help focus the thinking to these important considerations. As a consensus develops on these operational design considerations, objective guidance will follow.

8.4.1 Schedule

Audits are most effective in the initial phases of monitoring programs. It would be useful to have an audit concurrent with the initial field calibration. The audit methods might be carried out by the operators with the auditor assisting and making an independent report of the findings.

The optimum frequency of an audit is dependent upon the findings as they affect data validity. When the effort of the operating organization provides all the technical oversight to assure data reliability and validity, the audit becomes simply an independent statement to that effect. When the operating organization falls short of that goal, the audit becomes a motivation for improvement. A six month frequency should be adequate for audits. This provides a beginning, a mid-point check and a final check for a one year monitoring program. The audits will comment on the calibration performance and coupled with experienced data quality control, become a basis for legal claim to data validity. The independence of the auditor is critical to the legal claim of validity without operational bias.

8.4.2 Scope

The scope of the audit is discussed above in Section 8.4. An audit must begin with a briefing which states the goals of the audit, the methods to be employed, and the work required from the operator in assistance to the auditor. This should include a specific requirement for the operator to remove the anemometer, wind vane and temperature instruments from their mounts, after as-found observations are made, and connect them back to the system in a sheltered work place. A field audit (or calibration, for that matter) should be as close to a laboratory test as conditions allow. It is not acceptable to merely audit at the top of a 10 meter mast or 60 meter tower. When the audit is completed, an exit interview is required. Management level people should be present at both the initial briefing and the exit interview.

8.4.3 Audit Report

The audit report is the evidence of the audit. It must be complete and submitted in a timely manner, within 30 days of the audit performance. The findings should be as objective as possible but subjective judgments are valuable, particularly in those areas mentioned above that fall between the purview of the system audit and the performance audit. Where possible the audit report should contain copies of the forms used in the audit rather than, or in addition to, summarizations of the findings.

8.4.4 Audit Responses or Corrective Action

An audit is not worth the cost if there is not the support from the management of the operators to react promptly to required corrective action. The highest priority must rest with the performance audit findings where questionable data are being collected. Immediate corrective action is required before the collection of data can be considered useful.

8.5 Operational Checks and Preventive Maintenance

There may be little difference between operational checks and calibration checks. If the same person performs both functions, they may both be considered calibration checks. As such they deserve high credibility with respect to data validity. It may be the case, as it often is, that other measurements (such as air chemistry) are made at the same station. These instruments usually require more frequent attention than do the meteorological instruments. As long as the visit takes place, some attention to the meteorological instrument is advisable. The following sub-sections will assume that the frequent visitor to the station is a different person from the one who calibrates the meteorological instrument. The checker requires training to properly check the meteorological system.

8.5.1 Visual Inspection

A look at the anemometer and vane, probably through field glasses is desirable. Look for any evidence of physical damage or abnormal condition. For example, if icicles are hanging from the cups or vane, it should be communicated to the operator and noted in the log.

A diagram showing switch positions for normal operation should be posted near the system electronics. The person visiting for other reasons should check to see that the switches are in the correct positions. If not, contact should be made with a knowledgeable operator before changes are made. The observation, consulting information and consequent action must be entered in the log.

8.5.2 Manual Inspection

There should not be any manual (hands-on) inspection of the meteorological instrument by persons not qualified to perform calibrations.

8.5.3 Recorder Inspection

If the system has an analog recorder, the person visiting for other purposes should check the recorded data for signs of malfunction. If problems are found, contact the operator and decide what the appropriate action might be.

Unwind the strip chart so that the previous 24 hours can be seen. Look at the range of values recorded. Does it look reasonable or does there seem to be a limit on the high or low end of the trace? Check the nature of the speed and direction fluctuations. During the day there should be more wiggles (more turbulence) than at night. If the trace is always steady it might be a sign of excessive pen weight or a defective sensor. Check to see that the marking method (inking, for example) is working reliably and that supplies are sufficient to last until the next scheduled service visit. Check the paper drive to be sure that the chart is moving accurately with time and that the sprocket pins are engaged in the paper drive holes. Check the time marks on the chart to be sure they are correct. Mark on the chart a note indicating who and when this check was made. Also note in the log book that the check was made. Rewind the strip chart and make sure that it is moving correctly before leaving.

If there is another indication of wind meteorological outputs in the system, a meter or a digital readout for example, note the values on the strip chart. They may or may not agree exactly because of averaging time constants, but they should agree generally. If they do not, watch the meter for a few minutes and note a few values on the chart paper. If there is still not agreement, call the operator and report the finding and note it in the log. A visual examination of the direction the wind vane is pointing may also be used to independently check the recorder output, provided that the wind direction is fairly steady. This check will detect slippage in the alignment of the wind direction sensor due to a loose collar.

8.5.4 Preventive Maintenance

8.5.4.1 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.

8.5.4.2 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 sigma theta is calculated, the noise will bias the sigma value toward a higher value. It will probably not be possible to see early appearance of noise in the sigma data. When it becomes obvious that the sigma 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 sigma theta 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.

8.5.4.3 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.

8.5.4.4 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.

8.5.4.5 Precipitation

The gage 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 1/2 inch above the level of the orifice, with the orifice centered within the screen.

8.5.4.6 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.

8.5.4.7 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

The data collected by an on-site meteorological monitoring program must be validated prior to their use in air quality modeling analyses. The data validation process should consist of a review of the data by experienced personnel, a screening of the data to identify possible incorrect values, and a comparison of randomly selected data with other available data. These procedures, if followed, will help to identify problems within the monitoring program which escape detection by other quality assurance checks.

8.6.1 Manual Data Review

Soon after the meteorological data have been collected, a hard copy of the 15-minute or 1-hour averaged values should be reviewed by experienced personnel. The 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 as to the causes.

8.6.2 Data Screening Tests

The data should then be run through a screening program. This involves comparing the measured value with some expected value or range of values. The range test, in which data are checked to see if they fall within specified limits, is the most common and simplest test. The limits are set usually based upon historical data or physically realistic values. In a similar test, the rate of change test, the difference between the current measured value and the value from the previous time period is compared with physically realistic values. Suggested screening criteria are listed in Table 8-1. Other values may be more appropriate for a given location, therefore site-specific screening values should be developed by

Table 8-1
Suggested Data Screening Criteria*

Meteorological Variable	Screening Criteria
	Flag the 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/m or less than -3.0°C/m
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

*Some criteria may have to be changed for a given location.

an experienced meteorologist. If the data do not fall within the screening criteria, the data should be flagged for further investigation. Relationships between different variables should be considered in evaluating flagged data. Conditional flags may also be developed to account for these relationships in the screening program, e.g., comparing temperature and dew point during precipitation events, or checking for low wind speeds during highly variable wind directions.

8.6.3 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.

8.6.4 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 6.5.3). 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.

8.7 Recommendations

It is recommended that the quality assurance (QA) program for an on-site meteorological monitoring system should follow a QA plan that has been approved by appropriate project or organizational authority. The QA function should be independent of the organization responsible for the collection of the data and the maintenance of the measurement systems.

To insure that instrumentation of proper accuracy and response characteristics are purchased, procurement documents for meteorological monitoring systems should include the specifications required for the applications of the data (see Section 5.0), along with the test method by which conformance with the specification will be determined. The procurer should review the manufacturer's documentation of the tests used to demonstrate an instrument's conformance to specifications. An instrument should undergo an acceptance test to verify that it performs as the manufacturer claims, assuming that the specifications are correct. These acceptance tests should be similar in scope to a field calibration.

Routine system calibrations and system audits should be performed at the initiation of a monitoring program 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.

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 reasonableness of data and periodic preventive maintenance measures. The latter should include periodic checks of wind speed and direction bearing assemblies, cleaning of aspirated shield screens in temperature systems, removal and recharging (at least quarterly) of lithium chloride dew cells, cleaning the mirror in cooled mirror dew cells, clearing the precipitation gage 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 a visual scanning of the data for reasonableness, and automated screening and comparison checks to flag out-of-range or unusual values. This review should be performed at least weekly, and preferably on a daily basis.

9.0 REMOTE SENSING - DOPPLER SODARS

In recent years, Doppler SODAR (an acronym for Sound Detection And Ranging) systems have gained recognition as effective tools for remote measurement of meteorological variables at heights up to several hundred meters above the surface. There has been an increased interest in using SODARs to develop the meteorological data bases required as input to dispersion models. While SODARs in rare cases have been approved and used for this purpose, there is a distinct void in terms of the guidance needed to help potential users and the regulatory community alike develop acceptable on-site meteorological measurement programs with SODARs. The purpose of this section of the document is to provide a first attempt at filling this void.

Two intercomparison experiments, carried out in 1979 and 1982, compared winds measured by Doppler SODAR systems manufactured by four different companies against tower measurements at the Boulder Atmospheric Observatory (BAO).[45,46] The results of the intercomparison experiments were quite encouraging for mean winds. All four systems demonstrated virtually no bias for wind speed and direction, and scatter was in a range that might be expected, given that the SODAR systems were measuring winds in volumes of air displaced in space and time as opposed to the single-point tower measurements. Turbulence measurements were not as encouraging (see the discussion on this topic later in this section) although they do hold some promise.

While encouraging, the BAO intercomparison results should not be regarded as an unqualified endorsement of SODAR technology. Meteorological conditions during the test and characteristics of the BAO site were close to ideal for optimal SODAR performance. Furthermore, manufacturers operated their own systems and were given the opportunity to submit only data that they believed were valid. Many real-world applications involve conditions that may produce return spectra that are interpreted as valid when in fact they are not, such as high background noise, electrical interference, and ground clutter. Careful attention to siting requirements and data validation procedures is necessary to successfully overcome these real-world problems.

Doppler SODARs operate on a fundamentally simple principle, yet the systems that control their operation are quite complex. Thanks to diligent work on the part of SODAR manufacturers, systems have been engineered to operate reliably and with relatively little operator interface. However, the potential user should be aware that unattended and/or careless operation of a SODAR could result in the collection of erroneous data. Diligence and close scrutiny of the data on a regular basis, by someone experienced in meteorology and trained to recognize instrument problems, is a necessity (this is true for any meteorological measurement system, but particularly so for SODARs).

It should be noted that SODAR systems made by different manufacturers differ greatly in the generation of transmit pulses and in analyzing and processing return echoes from the atmosphere. It is not yet possible to make definitive recommendations as to which system works best in specific applications. Because of these differences (and because of the unique nature of Doppler SODARs), guidance provided herein is more generic than in previous sections. Specific operating procedures and quality assurance plans prepared based on this guidance and on other case-specific factors should provide feedback so that the guidance can be expanded and improved based on experience. The guidance may also be expanded or modified based on further controlled tests of Doppler SODARs that may be conducted at BAO in the future.

Such tests are anticipated to evaluate developments in SODAR technology designed to yield better turbulence measurements and the performance of automated data validation routines.

The development in recent years of "mini-SODAR" technology[47] represents a somewhat different approach to remote acoustic sounding, involving a phased array of speakers in place of a large transducer and antenna, and operating at much higher frequencies than more conventional SODARs. This technology allows measurements to be taken much closer to the surface than with more conventional SODARs, but is considered to be a research tool at this time. The information presented in the rest of this section is applicable primarily to more conventional SODARs, represented by the types of instruments tested in the BAO intercomparison experiments.

9.1 SODAR Fundamentals

The requirements for installing and operating a SODAR and for developing a modeling data base flow directly from the requirements for obtaining a good single pulse return from one antenna. This section discusses the SODAR fundamentals involved with getting a good signal return. An understanding of these fundamentals will help in understanding what needs to be done to develop an acceptable data base.

A SODAR transmits a strong (typically 100-300 watts) acoustic pulse into the atmosphere and listens for that portion of the transmitted pulse that is scattered and returned. A monostatic system uses the same acoustic driver both to transmit the pulse (driver acting as a powerful speaker) and to receive the return signal (driver acting as a sensitive microphone). A bistatic system uses different antennas to transmit and receive. Monostatic systems generally have collocated antennas while a bistatic configuration generally requires that the antennas be separated by a distance (typically several hundred meters) that is determined by the height at which measurements are desired. This section is concerned primarily with the most common Doppler SODAR configuration, namely a collocated monostatic system.

A volume of air will scatter incident acoustic energy. Most of the scattering occurs in the direction of propagation, but a small percentage of the energy is scattered back to the source. Scattering is due to wind speed and temperature discontinuities in the volume of air. An equation has been developed[48] that expresses the amount of scattering as a function of the angle measured to the direction of propagation of the transmitted pulse, and the velocity and thermal structure functions, C_V^2 and C_T^2. The structure functions can be interpreted as expressing the degree of instantaneous velocity or temperature difference between points a unit distance apart. If the direction of propagation is 0° and scattering directly back to the source is 180°, the following generalizations can be made based on the scattering equation:

1. There is no scattering at 90° or 270° (right angles);

2. Scattering at 180° is due to C_T^2 only, where C_T^2 scattering is a maximum;

3. Scattering at intermediate angles is due to both C_V^2 and C_T^2; the contribution from C_V^2 reaches a maximum at 135°.

Return signal strength for a bistatic system thus depends on both C_T^2 and C_V^2, while the strength of the returned signal for a monostatic system depends only on C_T^2. Scattering is accomplished by temperature variations on a spatial scale of one-half of the wavelength of the transmitted sound, approximately 10 cm for a SODAR operating at 1500 Hz.[49] The return signal is scattered from many of these small "targets" in the atmosphere.

The existence of atmospheric targets for a monostatic SODAR depends on the presence of a temperature gradient and small-scale turbulence that creates local instantaneous temperature differences much greater than the mean temperature gradient. A strong return signal can be produced either with an unstable potential temperature gradient and little wind shear (in a convective boundary layer) or with a stable potential temperature gradient and large wind shear (in a stable boundary layer). Fortunately for the science of doppler SODARs, C_T^2 never disappears entirely and, although a diurnal pattern of signal strength does occur, adequate targets are available most of the time.

Although a strong signal return indicates the presence of many atmospheric targets, it does not by itself signify that mixing is occurring on a scale that would diffuse the plume from a pollutant source. It is through the analysis of time-height patterns of signal strength, generally displayed on an analog facsimile chart, that mixing height information is inferred (see the later discussion on mixing heights).

The real strength of a SODAR system (for developing modeling data bases) lies in its ability to detect shifts in the frequency of the transmitted acoustic pulse. Frequency shifts are caused by the Doppler effect and are directly proportional to the speed of an air parcel moving away from (lower frequency) or towards (higher frequency) the transmitting antenna. If the antenna is tilted away from the vertical, simple trigonometry can be used to calculate the horizontal component of the motion of a parcel of air. If the return pulse is analyzed at different times following pulse transmission, speeds can be assigned to different heights above the surface based on trigonometry and the speed of sound. Many pulses can be averaged at each height to get an average speed for a time interval as a function of height. A second tilted antenna will produce a second (orthogonal) component. Vector wind direction and speed can be calculated from the two components at each level. Wind fluctuation statistics can then be calculated from the two components at each level along with the mean values.

Most monostatic Doppler SODAR systems (referred to henceforth in this section simply as SODARs) include a third, vertically-pointing antenna that measures vertical motion (mean and standard deviation) and also produces a time-height display of signal strength on a facsimile chart. Maximum heights and averaging intervals are generally user-selectable and typically range up to 1500 meters and from 2 to 60 minutes. The minimum SODAR wind level is 30-50 meters. Lower heights are not possible because of the time required for the diaphragm in the acoustic driver to come to rest and for the driver to be switched from the transmit to the receive mode.

The three antennas generally are not pulsed simultaneously. If they were, they would be listening to each other's return signals, and therefore they are pulsed sequentially. Furthermore, since an antenna must continue listening until it receives a return signal from the maximum height, setting the SODAR to higher heights reduces the effective sampling rate. At 600 meters, the effective sampling rate for each antenna is approximately once every 13 seconds.

A conclusion that can be drawn from the foregoing discussion is that the success of a SODAR hinges primarily on its ability to extract a peak frequency (single or double) from the return signal, as well as its ability to transmit a pulse with a sharply defined and precisely known peak frequency. Figure 9-1 illustrates what an ideal signal return might look like for one single-peak pulse. Frequency is plotted on the abscissa, amplitude on the ordinate. The graphs represent a "snap-shot" of the return spectrum at times following pulse transmission corresponding to 60 and 600 meters above the surface. What is shown is a sharp peak in the spectrum, a high signal-to-noise ratio, and no other interfering peaks. The attenuation of the return signal with height is also shown.

Acceptability of the return pulse depends in part on a strong, clear, concentrated transmit pulse. The pulse is created by a heavy-duty acoustic driver that is mounted above the parabolic dish. The antenna dish focuses the pulse and gives it its direction and inclination. A sound-deadening enclosure for the dish is required to reduce side-lobe effects, prevent ambient noise from reaching the microphone when the driver is in the receive mode, and to reduce the amount of nuisance created by the transmit pulse.

Given a good transmit pulse, there are still other sources of interference that can influence the quality of the data extracted from return spectra. The unique nature of SODARs for measuring meteorological variables lies in the fact that a SODAR is a remote measurement device that probes the medium (the atmosphere) and actually measures only the response to that probe. Data quality therefore is related to the probe itself and to the fact that the nature of the probe (acoustic energy) is such that there can be many sources of interference. This can be contrasted to a wind vane which is located in the medium that it is measuring. Sources of a voltage that could be interpreted as an erroneous wind direction signal from a wind

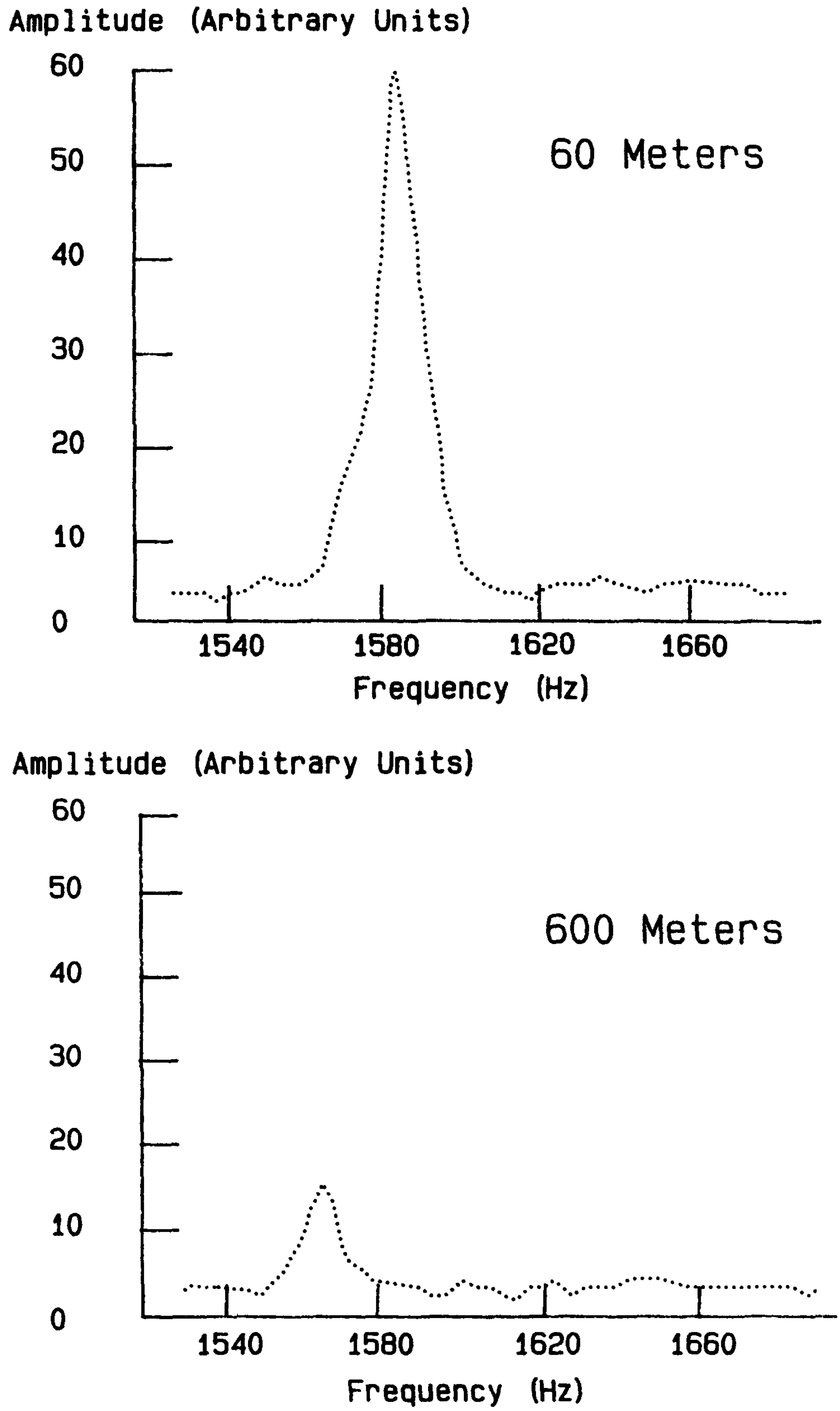

Figure 9-1. Example SODAR Return Spectra

vane are much fewer than potential sources of interference for a SODAR.

A successful SODAR-based measurement program depends on maximizing the occurrence of "ideal" spectra such as discussed above, minimizing the number of times when data is lost due to high background noise (low signal-to-noise ratios), minimizing the number of times when interfering signals are interpreted as atmospheric returns (thereby producing erroneous data), and validating the data to ensure that erroneous data do not enter the data base. The rest of this section presents guidance on how to develop an operational plan to achieve these ends. The operational plan addresses siting and ex-exposure, operation and maintenance, quality control, quality assurance, data validation, data management, and data use.

It is important to again note that different SODAR manufacturers have designed their systems with different techniques for producing transmit pulses and for extracting the atmospheric signal from return spectra. Therefore, different systems have different means of discriminating acceptable spectra. The techniques described herein for maximizing valid data capture will have a different emphasis based on the system chosen. An operational plan, including Standard Operating Procedures and a Quality Assurance Plan, can therefore differ between systems. The manufacturer may already have developed most of the information required for the plan. Nonetheless, each of the aspects of this plan, as discussed in this document, should be addressed in some fashion and agreed to between applicant and regulatory agency, prior to the start of data collection.

9.2 Siting and Exposure

The fundamental requirement of a return signal with a sharply defined atmospheric peak frequency places special requirements on the siting of a SODAR. Siting criteria described elsewhere in this document should be followed in general; in addition, the other factors discussed here that are unique to SODARs must be assessed.

External noise sources can be classified as active or passive, and as broad-band (random frequency) or narrow-band (fixed frequency). General background noise is considered active and is broad-band. If loud enough, it can cause the SODAR software to reject data because it can't find a peak or because the signal-to-noise ratio is too low. The net effect is not to produce erroneous data but to lower the effective sampling rate due to the loss of many of the pulses. The manufacturer should be consulted as to what noise level would be acceptable. A qualitative survey should be conducted to identify potential noise sources, and a quantitative noise survey may be necessary to determine if noise levels are within the manufacturer's minimum requirements.

Examples of active, broad-band noise sources include highways, industrial facilities or power plants, and heavy machinery operating near the SODAR. Some of these noise sources have a pronounced diurnal, weekly or even seasonal pattern (farm machinery, for example). The noise survey should at least cover diurnal and weekly patterns. Examination of land-use patterns and other sources of information may have to be relied on to determine if any seasonal activities would be a problem. A noise survey will not cover all bases, but a carefully designed survey should help decide if a site is suitable.

Examples of active, fixed-frequency noise sources include rotating fans, the back-up beeper on a piece of heavy equipment, and birds and insects. If these noise sources have a frequency component in the SODAR operating range, they may be picked up as good data by the SODAR. Some of these sources can be identified during the site selection process. Problems can be avoided by taking precautions such as pointing the antennas away from the instrument shelter (where the sound of an operating air conditioner might be picked up). Wind blowing over the enclosures and rain impacting on the horn or enclosure also represent noise sources that may affect data capture.

One approach to reducing the problem of fixed frequency, narrow-band noise sources is to use a coded pulse, i.e., the transmit pulse has more than one peak frequency. A return pulse would not be identified as data unless peak frequencies were found in the return signal the same distance apart as the transmit frequencies.

Passive noise sources are objects either on the ground or elevated (such as tall towers, electric power transmission lines, buildings and trees) that can reflect a transmitted pulse back to the antenna. While most of the acoustic energy is focused in a narrow beam, side-lobes do exist and are of particular concern when antenna enclosures have degraded substantially. Side-lobes reflecting off of stationary objects and returning at the same frequency as the transmit pulse may be interpreted by the SODAR as a valid atmospheric return with a speed of zero. It is not possible to predict precisely which objects may be a problem. Anything in the same general direction that the antenna is pointing and higher than 5 to 10 meters is a potential reflector. It is therefore important to construct an "obstacle vista diagram" prior to SODAR installation that identifies potential reflectors and their height as a function of direction from the antenna. This diagram can be used after some data have been collected to assess whether or not reflections are of concern at some SODAR height ranges. It should be noted that reflections from an object at distance X from an antenna will show up at a height X cos(theta) where theta is the tilt angle of the antenna from the vertical.

An approach to dealing with the problem caused by fixed echoes is to utilize software that eliminates signal returns where the peak frequency is the same as the transmit frequency. This technique can also recognize a zero Doppler shift caused by antenna "ringing", where the speaker diaphragm, or driver mounting hardware continues to vibrate after the driver has been switched to the receive mode. The potential for rejecting valid zero Doppler shift returns would have to be addressed when utilizing this type of software.

The mobility of trailer-mounted SODARs allows them to be set up and operated in a temporary mode with very little site preparation. For installations where a long-term data base is desired, the SODAR should be installed on a more permanent base such as a concrete pad.

The two horizontal antennas should be aligned and tilted carefully, as small errors in orientation or tilt angle can produce unwanted biases in the data. True North should be established based on one of the techniques described in the Quality Assurance Handbook for Air Pollution Measurement Systems: Volume IV, Meteorological Measurements.[3] Orientation of the SODAR antennas should be based on the axis of the parabolic dish that focuses the sound pulse. Since the dishes are hidden from view by the antenna enclosures, orientation is commonly accomplished with reference to the trailer or the enclosure sides. This is acceptable as a quick check, as long as the measurement that is taken on the trailer or enclosure side is related to the measurement that is required (relative to the antenna dish) on a periodic basis.

Another siting concern that is unique to SODARs relates to the fact that wind measurements are a composite of two independent measurements of air parcels separated in space. For typical height ranges the parcels may be separated by several hundred meters, depending on the antenna tilt angle and the measuring height. In complex terrain, the different parcels may be in different flow regimes. A topographic map should be used to "plot" air parcels based on antenna geometry, and the location of the parcels relative to terrain should be evaluated.

One last item that should be considered in a SODAR siting decision is the effect of the instrument on its surroundings. The sound pulse is quite audible and could create a disturbance if antennas are located too close to residences.

9.3 Operation and Maintenance; Quality Control

Detailed operation and maintenance (O&M) procedures are specific to each manufacturer's instrument. This section discusses O&M procedures in general and recommends elements that should be addressed in any SODAR O&M plan.

When setting up a SODAR for operation in the field, it is important to consider several factors when selecting the averaging interval and height range. Predicted plume heights of sources to be modeled is one factor. The effective sampling rate is another factor that should be considered (higher heights result in fewer transmit pulses). The height and averaging interval settings should initially be fixed at some nominal values, such as 600 meters and 15 minutes. A different height can be specified, but it is suggested that 300 meters be the minimum height.

The Quality Control (QC) function is closely related to operating procedures which should provide for data review as well as site visits. The procedures developed for a specific instrument at a specific site should be written up in a standard operating procedures document (SOP) that can help ensure that all important aspects of SODAR operation are checked at regular intervals, and that other procedures for data review and management are being followed. There are not many example SOPs available. As more SOPs are developed, a greater body of knowledge will be available to build on. Manufacturers can also provide a great deal of information that can be incorporated into a site-specific SOP.

The purpose of an SOP is to spell out operating and QC procedures with the ultimate goal of maximizing valid data capture. The keys to a successful SODAR QC program, based on the experience of many users, are (1) timely data review by an individual with meteorological expertise and SODAR experience and (2) diligence in regular checking of all aspects of SODAR operation under the direction of highly qualified electronics personnel.

It is helpful here to recall the fundamentals of reliable SODAR operation; a clear, sharp transmit pulse with sharp frequency peak(s), and return spectra with low background noise and well-defined frequency peak(s) due to atmospheric echoes. Departures from this ideal can produce either erroneous data or a severe loss of data. Some departures from the ideal will occur in any SODAR data base; a later section will discuss refining and validating that data base. Timely data review and regular site checks will serve both to identify and fix "fatal flaws", and to minimize to the greatest degree possible, the amount of data that has to be "weeded out". The type of system that is used also affects the degree to which data must be validated.

A "fatal flaw" can include an instrument failure which is the most obvious problem to identify (i.e., no data are being produced). Another fatal flaw might be the complete or partial failure of one of the acoustic drivers. Data would still be collected if this occurred but with one component missing. If this was a horizontal component, the data would be virtually useless. Data capture from one antenna might degrade to the point where it is almost entirely missing, if the diaphragm in that driver is on the verge of failure or if snow and/or ice has built up to a significant degree in the antenna dish (remember that the parabolic dish shapes and focuses the transmit pulse - snow and ice build-up will distort the pulse). An antenna dish heater is recommended to reduce this problem in locations where frozen precipitation can occur. Mechanical relays that switch drivers from the transmit to receive mode can also fail causing a loss of data.

Timely data review and regular site checks can also serve to identify "non-fatal" flaws. Non-fatal flaws generally are data anomalies that would cause some levels of data to be invalidated but not enough to consider the period "missing". Echoes that occur intermittently should be noted. Antenna ringing, caused by continued vibration of a component in the driver or on the driver mounting hardware after the driver has been switched to the receiver mode, will show up as zero's in the lower levels of the data. Periods of data loss that are not otherwise explainable may help identify noise sources not previously identified (farm machinery operating near the site, for example).

Some "non-fatal" flaws can be fixed, others cannot. Flaws that can't be fixed should be noted for the final validation process. Problems that are persistent should be tracked down, although sometimes this is not possible because the problem doesn't occur when help is available to track it down. The main objective of the timely data review/regular site check process is to keep the non-fatal flaws from becoming fatal flaws which would translate into substantial data loss.

An SOP should be tailored to a particular instrument at a particular site. What follows is a description of major elements of data review and site procedures that should be addressed in any SOP.

Data Review

° Ideally the data should be spot-checked on a daily basis (this is generally possible only for sites with a remote interrogation capability);

° A more complete data review should be conducted on a weekly basis. The following types of data reports have been found to be useful:
  - component-specific reports that display time-series of the data profiles for each component (mean and standard deviation);
  - printouts that group many averaging periods on the complete data set on one page;
  - hourly averaged data displayed in manner that will highlight diurnal patterns; and
  - summaries of raw frequency data analyses.

° On a monthly basis preliminary data capture summaries should be prepared on a component-specific basis and for resultant data.

° A tower (at a minimum of 10 meters) should be installed at the SODAR site. A tower would generally be required to provide surface data as input to stability determinations, but can also be valuable in the QC process. A measurement system capable of providing u and v components at the same time as the SODAR data is preferred. Some manufacturers offer a 10-meter tower as an integral part of their SODAR systems. In complex terrain, siting of the tower may be problematical and its usefulness may be limited as a result.

Site Visits

° Perform instrument diagnostics as specified/recommended by the manufacturer.

° Obtain printouts of data collected during site visit and provide qualitative description of how well actual site conditions are reflected by the data. NOTE: This could include making observations of stack plume direction and amount of plume rise, comparison of SODAR data to tower data, etc.

° Check operation of facsimile chart recorder; provide description of how well actual site conditions are reflected in the data - primarily cloud cover, time of day, wind speeds.

° Inspect all antennas for accumulation of snow (which may indicate faulty heater cables), and birds or insects present inside enclosure. Listen to several pulses from each antenna to verify that the driver is in good shape.

° Collect raw frequency data, if done as part of the QC process.

- Remove and replace magnetic tape, if being utilized.
- Site visits should be made frequently enough that data capture objectives can be met. The frequency of visits may depend on how much information on SODAR operations can be obtained by remote interrogation.

9.4 Quality Assurance

Major elements of a SODAR Quality Assurance (QA) plan are: QC procedures, periodic audits, and data validation. QC procedures are discussed in the previous section in the context of an SOP. Data validation is discussed in the next section on data use, and audits are discussed here. It is quite important for all three elements to be present. An audit by itself can ensure that the instrument is operating correctly at the time that the audit is conducted. Comprehensive QC procedures (carried out through site visits and data review) are necessary to ensure that good data are collected between audits, and data validation is necessary to ensure that anomalous data do not enter into a final data base used for modeling.

SODAR audits should be conducted when the system first begins on-site operation and every six months thereafter, although some elements do not have to be repeated at each audit. Specific procedures will vary among manufacturers, but the four main elements are as follows: site evaluation, internal and external instrument checks, a system audit and a performance audit. These terms are somewhat loosely defined here; some overlap is possible in the elements as stated.

Site Evaluation: The SODAR site characteristics in terms of noise potential, both active and passive, should be evaluated and documented (refer to the previous discussion on siting and installation).

Internal and External Instrument Checks: Some of these checks should mirror the checks made on a routine basis, and some are quite specific to each instrument. Some of the checks that can be made are for electronic noise, local oscillator frequency, ramp and amplifier gain circuits, and automatic gain control circuits. An effort should be made to check the circuits that control the transmit pulse frequency, particularly if that frequency is adjusted from one period to the next. Accurate transmit frequency is directly related to data accuracy, since speed computations are based on the frequency shift of the measured return peak frequencies where the transmit frequency has to be assumed.

External checks should also be carried out and should also mirror to some extent the routine checks. Each antenna should be examined, the enclosure lining material checked, and the tilt and orientation measured. Transmit pulses from each antenna should be listened to, to determine if the acoustic drivers are functioning properly.

Facsimile chart records, if collected, should be examined to determine if conditions recorded on the charts reflect actual conditions for the day. Charts should be reviewed for some time period prior to the audit to identify potential large periods of missing or invalid data.

Acoustic pulses of known frequencies may be used to determine if the SODAR correctly detects and interprets frequency shifts in the return signal. This technique, known as static calibration, tests portions of the SODAR's electronic circuitry, but does not test a system's ability to extract a valid Doppler shift from a return signal that contains background noise or to identify the presence of fixed echoes or electronic interference.

System Audit: This should include a review of data handling procedures and conformance to site inspection and data review procedures. Since what happens in between audits is a critical element of a successful SODAR program, the audit itself provides a good opportunity to critically review conformance to the data review and site inspection requirements of the SOP. As part of a system audit, data should be produced and reviewed in the same manner as for the QC checks.

Performance Audit: The site evaluation, internal and external intrument checks, and system audit ensure that the SODAR is being operated correctly. A performance audit compares SODAR wind measurements with an independent measurement. SODAR performance audits should consist of comparing data on a component-specific basis, as well as comparing resultant speed and direction. Any one of the following approaches to testing SODAR performance may be considered:

1. Use of a temporary measurement system such as a tethersonde or kite anemometer. Data from this test should cover as many meteorological conditions as possible. A sample size of 120 15-minute samples would generally be considered adequate. The independent measuring technique should be used to collect data for a full averaging period at one height, rather than measuring at several heights during the period. Samples should be taken at several heights during the course of the audit.

2. Use of a fixed tower measuring data at an elevation corresponding to an elevation measured by the SODAR. A tower that utilizes terrain to achieve part of the elevation may be acceptable in some situations (refer to Section 3.2 for a discussion of this issue). Since a tower provides a continuous measurement, the data produced can actually serve two purposes.

First, the data can be used in the performance audit by comparing SODAR to tower measurements for a period of time corresponding to the audit (nominally one week of continuous data), and also for the period of time since the last audit. Second, the data can provide a valuable input to the QC process, as a continuous check on SODAR performance.

3. Use of a second SODAR operating at a different transmit frequency. Not many tests of this type have been carried out. The advantages include being able to provide comparisons of complete profiles and being able to provide comparisons continuously for the period of the test. A nominal testing period of one week of continuous data is suggested as a minimum.

The following factors should be considered when conducting a performance audit:

- ° Good comparisons between SODAR and tethersonde/kite anemometer systems give confidence that both systems are working well. Bad comparisons, on the other hand, do not necessarily mean that the SODAR is faulty, rather, it could mean that the alternate measurement technique is faulty or that the difference in measurement techniques simply produce different values for the conditions measured. The usefulness of such a test is therefore limited by the potential to produce results that are not meaningful.
- ° Tethersondes and kite anemometers are limited to daytime use. For applications where nighttime, stable conditions are important, a performance test such as this is not useful for determining whether these conditions are adequately measured.
- ° The continuous one-level comparison provided by the 10m tower can provide a means of continuous comparison with an independent

measurement. It is important to understand that the tower is not measuring the same thing as the first acoustic level, and therefore cannot replace the performance audit. However, evaluating the complete profile on both a resultant and component-specific basis can contribute to an assessment of the accuracy of the acoustic portion of the data. This assessment is particularly useful when evaluating profiles measured in well-mixed, neutral atmospheric conditions. Severe terrain in the immediate vicinity of the SODAR site will limit the usefulness of this comparison.

A performance audit should be performed at the beginning of a SODAR measurement program, and at least annually thereafter. As stated above, other portions of the audit should be conducted at six month intervals.

9.5 Data Validation, Data Management and Data Use

9.5.1 Data Validation

A carefully sited, well-maintained SODAR will produce high quality data most of the time. Since the SODAR can occasionally misinterpret interfering signals and assign "valid" codes to the resulting data, validation is an important step in developing a modeling data base. The degree to which validation and post-processing is necessary depends partially on the site but also on the system being used - some SODARs are more selective than others in accepting return pulses, and some SODARs are being introduced with built-in validation software.

Section 9.1 describes the types of anomalous data that can occur. Final validation should not occur until after at least one complete audit has been conducted, although "fatal flaws" (which would invalidate an entire data period) should be removed from the data base shortly after they are discovered.

It is not possible to provide specific guidance on SODAR data validation procedures at this time. The following are suggested steps that would need to be enhanced (and could be modified) for a particular system and a specific application.

1. Data should be reviewed by a meteorologist familiar with SODAR operation soon after they are collected, on at least a weekly basis. Fatal flaws should be identified and removed.

2. A screening program should be developed that produces flags for each level on each antenna. The flags could be assigned based on the amount of shear between levels, the value of the radial standard deviation, and other values that characterize anomalous data (refer to Section 8.6). The flags should be numeric (possibly 0-9) with values assigned on a sliding scale. For example, a value of 1 might be assigned to a difference between 2 levels of 2 meters/second, a value of 9 to a difference of 10 m/s. Likewise, a value of 1 might be assigned to a standard deviation of 1.5, a value of 9 assigned to a standard deviation of 3.0. Since perfect data may be equally suspect, a value of 9 might be assigned to a standard deviation of 0.0.

3. When the data with flags are reviewed (again by a meteorologist familiar with SODAR operation) the flags may be manually changed if the reviewer feels that the screening flags are inappropriate. This additional review is important, since the reviewer can rely on an assessment of the entire profile - something which is difficult to accomplish with a

computer program. It is also important to thoroughly document the changes and the rationale for the changes, such that an independent reviewer can distinguish between manual and automatic flags.

4. A final data base should be created by automated means, based on a test of the flags. The entire data base should be examined to determine what level should be accepted - a value of 2 or less might be accepted, for example, while a value of 3 or greater rejected.

5. Reserving final data validation until a full year of data has been collected will allow statistical and climatological summaries of the data to be prepared and further data checks to be made against other data sources (e.g., nearby NWS upper-air stations or nearby towers). This additional information can help in the validation process by providing a reference against which individual data points can be evaluated (for example, a profile initially thought to be an anomaly may occur several times and be traced to a real meteorological phenomenon).

9.5.2 Data Management

A SODAR produces a prodigious amount of information. If set at 600 meters, 15 minute averages, 30 meter increments with one tower level, several variables are produced and recorded at twenty levels. It is important to plan for managing these data prior to the start of the measurement program. The data management scheme should accommodate the following:

1. Initial checks to ensure that the data have been transferred correctly (i.e., that magnetic tapes can be read or data sets transferred by phone link are intact);

2. Quick data turn-around in a format that can be reviewed to identify fatal flaws and instrument problems that can be fixed. This is not a trivial task, and should include the following (as input to the QC procedures):

a. Reports that summarize profile data from each antenna on one line for each time period;

b. Reports that present a significant portion of the data from each time period (to cut down on the amount of paper produced, several time periods can be placed on one page);

c. Reports that present hourly averages in a format where diurnal patterns can be examined; and

d. Reports that summarize raw frequency data analyses.

3. A provision for editing the data if errors occur or as a result of the data validation process. All editing functions should be carefully controlled and documented; and

4. Methods for archiving the data.

9.5.3 Data Use

Several types of data are produced by a SODAR; furthermore, data availability can vary with height as a function of atmospheric conditions (the existence of suitable "targets") and ambient noise (more noise, less data). Three important questions that will be addressed in this section are: 1) which data types can be used in regulatory modeling; 2) what level(s) are appropriate to use in a dispersion model, and how are they to be used; and 3) how should data availability be defined (and what percentage of data capture is required).

9.5.3.1 Data Types

Mean Wind Values: Wind speed and wind direction values are reported for many heights. Based in part on the results of the BAO intercomparison results, the mean values are appropriate for use in regulatory modeling if the SODAR system is subject to an approved QA plan and the data are validated prior to use. Treatment of low wind speeds is an important consideration since the SODAR produces a vector-averaged speed. Mean vertical wind speed, a variable that is also reported by SODAR systems, is not yet used in regulatory modeling although the reported values may provide some meteorological insights.

Wind Fluctuation Values: Most SODAR systems report the standard deviations of horizontal wind direction (σ_A) and of vertical wind speed (σ_W). Values of σ_A from SODAR are usually much larger than values recorded by a wind vane, although the overestimation appears to lessen with higher wind speeds. A fundamental problem is that SODAR winds are composed of samples taken from different volumes of air at different times. Wind direction fluctuations cannot be calculated directly, and the estimation techniques tend to over-estimate the amount of fluctuation.

As a result of these concerns, σ_A data from SODARs are not being recommended for modeling use at this time. Some work has been done to develop corrections to SODAR σ_A data.[50,51] Furthermore, some manufacturers are exploring ways of designing the system to avoid the fundamental problem (e.g., using a configuration that that points to monostatic antennas at the same volume of air, pulsed at the same time but at a different frequency so that the signals do not interfere with each other).

The BAO results indicate that σ_W values do not compare with tower measurements as well as wind speed or direction, although daytime (convective) values show better agreement than nighttime (stable) values. In order to relate σ_W to diffusion, a transformation to σ_E (standard deviation of elevation angle fluctuations) must be made by dividing σ_W by wind speed (see Section 6.4.1). Since SODAR wind speed is a vector average, overprediction of σ_E is likely to occur under low wind speed conditions. Use of σ_W data from SODARs is also not recommended for regulatory modeling at this time.

An obvious point to make is that no model currently in Appendix A of the Guideline on Air Quality Models (Revised)[4] is capable of utilizing direct turbulence measurements. The purpose of including this discussion is that this guidance is also intended for applications where nonguideline models are being evaluated and there may be some nonguideline models that can utilize the turbulence data. Furthermore, models under development by EPA that utilize turbulence data may eventually be included in the guideline. This discussion is not meant to categorically deny the use of turbulence data from a SODAR. If an applicant wishes to use the data, it is up to the applicant to overcome the concerns expressed here. Further improvements in processing techniques, correction factors, or improvements in equipment may make SODAR turbulence data acceptable for regulatory modeling.

Mixing heights: The facsimile chart produced by a SODAR can be analyzed to estimate mixing heights. Mixing heights estimated in this manner are not recommended for routine modeling use, primarily because of height limitations. A typical convective boundary layer appears on the facsimile chart as a series of spikes ("thermal plumes"). Occasionally a limiting stable layer can be observed by a skilled analyst that can properly be interpreted as a limit to the vertical extent of mixing. More commonly, the elevated stable layer is not strong enough to produce an unambiguous trace or is out of range of the instrument (facsimile charts are generally set at 500 or 1000 meters). In this case the top of the visible thermal plumes does not necessarily indicate the vertical extent of mixing, just that the atmospheric targets are not strong enough to produce a visible trace at that height. (It should be noted that the dynamic response characteristics of the facsimile chart recorder are different from the part of the SODAR that interprets frequency shifts. Therefore wind data can be derived at heights well above the end of the visible trace on the chart recorder.)

If mixing heights are thus underestimated, their use in a model may lead to under- or over-predictions. This is because most EPA models employ the assumptions that ground-level concentrations are zero when a plume is above the mixing height, and that complete reflection of the plume occurs if the plume is below the mixing height.

As in the case of turbulence values, an applicant has the opportunity to use SODAR mixing heights if the concern expressed here is overcome. Use of the Holzworth interpolation[11] scheme with some of the facsimile information may have some promise. Manufacturers have recently begun to offer automatic mixing height detection routines. These routines should be examined carefully prior to approving their use.

SODAR facsimile charts can, on the other hand, provide valuable information on the condition of the atmosphere. Although translating that information into data usable in a regulatory context is problematical, the information could be used in a diagnostic sense when conducting a model evaluation study. Users are encouraged to develop schemes for using the data, although it should also be noted that facsimile charts are not easy to handle.

9.5.3.2 Levels for model input

Wind speed and direction data from many levels are available from a SODAR, and data are generally available well above the 100m level that is considered a practical limit for tower heights. A scheme for utilizing SODAR data for regulatory model input is recommended below. Other schemes may be approved on a case-by-case basis.

1. Wind data at stack top or at plume height may be used as input to regulatory models. Wind speed is generally used for plume rise and dilution calculations, and wind direction is used to determine plume transport direction. Selecting a single measurement height representative of average plume height under critical meteorological conditions is acceptable.

2. A SODAR measurement is derived from signal returns from a layer of the atmosphere, rather than a single level. The speed or direction values at one level are essentially averages across the layer. If the elevation of the measurement height selected for model input (stack top or plume height) is close to the elevation of the center of a SODAR range gate, then the data from that level should be used. If the height selected for model input is close to the upper or lower end of a range gate, then the speed and direction data should be interpolated between the two adjacent range gates.

3. If data are not available at the height selected for model input but the data period is considered valid as defined below in

Section 9.5.3.3, substitutions should be handled as follows. The wind speed at model input height may be determined from a logarithmic profile based on available data from at least three levels. Wind direction from the closest level with valid data may be substituted, as long as that level is at least at 100m. If the data are not available for these substitutions, or if the averaging period is not considered valid, refer to Section 6.5.3 for guidance on treatment of missing data.

4. An upper bound should be established for selection of a measurement height for model input. This is because data capture becomes more erratic at greater heights, and also because return signals are more saturated with noise at greater heights and erroneous data are more likely to occur. It is recommended that the cut-off level for model input be the highest height with data capture of at least 80%. See Section 9.5.3.3 below for a more complete discussion of data capture requirements.

9.5.3.3 Data capture requirements and definition

Data capture for a SODAR data base must be defined somewhat differently than for more conventional instruments. Data capture for SODARs is a strong function of height. A valid data period should not be defined in terms of a specific height because of the possibility that data at that height might be invalidated due to intermittent echoes. The following definitions and requirements should apply to SODAR data bases:

1. A SODAR averaging period will be considered valid if there are at least three complete (both components), valid levels for the period (independent of height). "Valid level" refers to data that have gone through final validation.

2. An hour will be considered valid if at least 30 minutes are valid (i.e., 2 out of 4 15-minute periods); and

3. Valid SODAR data as defined in (1) and (2) should be available at least 90% of the time on an annual basis.

9.6 Recommendations

Doppler SODARs can be used to provide mean wind speed and direction at heights not readily achievable by towers, and in some cases mixing heights, for on-site meteorological measurement programs. The turbulence data available from most SODAR systems are currently not recommended for routine use.

A proposal to utilize Doppler SODAR in an on-site program should be closely coordinated with the reviewing agency. An overall operational plan, including Quality Assurance procedures, should be prepared prior to data use and preferably prior to the start of data collection. The details of the operational plan will change with the specific instrument manufacturer. The following topics and recommendations should be addressed in the operational plan. The text of previous sections contains more detailed discussion on these topics.

Siting and Installation

- Noise survey: qualitative followed by quantitative if necessary
- Identification of potential reflection targets
- Disturbance potential
- Analysis of flow regime being measured
- Initial alignment

Operation and Maintenance; Quality Control (QC)

- Many aspects of O&M specific to manufacturer
- Initial settings of 15 minutes for averaging period and at least 300m for height.
- Collocated tower (at a minimum of 10 meters)
- Standard Operating Procedures:

  Timely and thorough data review: daily, weekly, monthly procedures

  Regular instrument checks (frequency based on degree of remote interrogation available)

Quality Assurance Plan

- Major elements are QC procedures, periodic audits, and data validation

- Audits should be conducted at six month intervals and should include:

  Site elevation
  Internal and external instrument checks
  System audit
  Performance audit: when instrument is placed in service and at least annually thereafter

Data Validation

- Should be carried out, on a component-specific basis, prior to using data in a model for regulatory purposes
- Procedures should be manufacturer-specific

Data Management

- Prodigious amount of information necessitates careful planning
- Management plan should incorporate timely review and archiving of data

Data Use

- Wind speed and direction recommended for use
- Wind speed and direction at stack top or at plume height for model input
- An upper bound should be established, where data capture is at least 80%, for developing model inputs
- Mixing height may be acceptable on a case-by-case basis

Data Capture Requirements

- Valid hours must be available 90% of the time
- Valid hour defined as at least three complete valid levels for 30 minutes out of an hour (two 15-minute values)

10.0 REFERENCES

1. Environmental Protection Agency, 1987. Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD). EPA-450/4-87-007. U. S. Environmental Protection Agency, Research Triangle Park, NC.

2. Federal Register 45:52676-52748. August 7, 1980.

3. Finkelstein, P. L., D. L. Mazzarella, T. J. Lockhart, W. J. King and J. H. White, 1983. Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements. EPA-600/4-82-060. U. S. Environmental Protection Agency, Research Triangle Park, NC.

4. Environmental Protection Agency, 1986. Guideline on Air Quality Models (Revised). EPA-450/2-78-027R. U. S. Environmental Protection Agency, Research Triangle Park, NC.

5. Strimaitis, D., G. Hoffnagle and A. Bass, 1981. On-Site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources-Workshop Report. EPA-600/9-81-020. U. S. Environmental Protection Agency, Research Triangle Park, NC.

6. American Nuclear Society, 1984. Standard for Determining Meteorological Information at Nuclear Power Sites. ANSI/ANS-2.5-1984. American Nuclear Society, La Grange Park, IL.

7. Mason, C. J. and H. Moses, 1984. Meteorological Instrumentation. In: Atmospheric Science and Power Production, D. Randerson (ed.). DOE/TIC-27601. U. S. Department of Energy, Oak Ridge, TN.

8. Great Britain Meteorological Office, 1956. Handbook of Meteorological Instruments, Part I. Her Majesty's Stationery Office, London, England.

9. Middleton, W. E. K. and A. F. Spilhaus, 1953. Meteorological Instruments, 3rd ed. University of Toronto Press, Toronto, Canada.

10. Wang, J. Y. and C. M. M. Felton, 1983. Instruments for Physical Environmental Measurements, 2nd ed. Kendall/Hunt Publishing Company, Dubuque, IA.

11. Holzworth, G. C. 1972. Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States. AP-101. U.S. Environmental Protection Agency, Research Triangle Park, NC.

12. Environmental Proteciton Agency, 1977. User's Manual for Single-Source (CRSTER) Model. EPA-450/2-77-013. U.S. Environmental Protection Agency, Research Triangle Park, NC.

13. World Meteorological Organization, 1971. Guide to Meteorological Instruments and Observing Practices. WMO No. 8TP3, 4th ed., Secretariat of WMO, Geneva, Switzerland.

14. Environmental Protection Agency, 1985. Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulations) - Revised. EPA 450/4-80-023R. U. S. Environmental Protection Agency, Research Triangle Park, NC.

15. Hanna, S. R., G. A. Briggs, and R. P. Hosker, 1982. Handbook on Atmospheric Diffusion. DOE/TIC-11223. U. S. Department of Energy, Oak Ridge, TN.

16. U. S. Department of Commerce, 1972. National Weather Service Observing Handbook No.2, Substation Observations. Environmental Science Services, Office of Meteorological Operations, Silver Springs, MD.

17. Raynor, G. S, P. Michael, and S. SethuRaman, 1979. Recommendations for Meteorological Measurement Programs and Atmospheric Diffusion Prediction Methods for Use at Coastal Nuclear Reactor Sites. NUREG/CR-0936. U.S. Nuclear Regulatory Commisison, Washington, DC.

18. Brooks, C. E. P. and N. Carruthers, 1953. Handbook of Statistical Methods in Meteorology, M.O.538. Her Majesty's Stationery Office, London, England.

19. Mazzarella, D. A., 1972. An Inventory of Specifications for Wind Measuring Instruments. Bull. Amer. Meteor. Soc., Vol. 53, No. 9. pp.860-871, American Meteorological Society, Boston, MA.

20. Gill, G. C., 1967. On the Dynamic Response of Meteorological Sensors and Recorders. Proceedings of the First Canadian Conference on Micrometeorology, Part I, Meteorological Service of Canada, Toronto, Canada.

21. American Society for Testing and Materials, 1985. Standard Method for Measuring Surface Wind by Means of Wind Vanes and Rotating Anemometers. ASTM D4480-85, American Society for Testing and Materials, Philadelphia, PA.

22. Mazzarella, D. A., 1978. Meteorological Instruments for Use Near the Ground: Their Selection and Use in Air Pollution Studies. In: Air Quality Meteorology and Atmospheric Ozone, Morris and Barris (eds.), American Society for Testing and Materials, Philadelphia, PA.

23. Snow, J. T., 1985. Meeting of ASTM Subcommittee D-22.11: Meteorology. Bull. Amer. Meteoro. Soc., Vol. 66, No. 11, p.1432, American Meteorological Society, Boston, MA.

24. Mardia, K. V., 1972. Statistics of Directional Data. Academic Press, New York, NY.

25. Turner, D. B., 1986. Comparison of Three Methods for Calculating the Standard Deviation of the Wind Direction. J. Climate Appl. Meteor., Vol. 25, pp 703-707.

26. Yamartino, R. J., 1984. A Comparison of Several "Single-pass" Estimators of the Standard Deviation of Wind Direction. J. Climate Appl. Meteor., Vol. 23, pp.1362-1366.

27. Irwin, J.S., 1979. A Theoretical Variation of the Wind Profile Power-Law Exponent as a Function of Surface Roughness and Stability. Atmos. Env., Vol. 13, pp. 191-194.

28. Paumier, J., D. Stinson, T. Kelly, C. Bollinger, and J. S. Irwin, 1986. MPDA-1: A Meteorological Processor for Diffusion Analysis - User's Guide. EPA 600/8-86-011. U. S. Environmental Protection Agency, Research Triangle Park, NC.

29. Weber, A., J. S. Irwin, J. P. Kahler, and W. B. Petersen, 1975. Atmospheric Turbulence Properties in the Lowest 300 Meters. EPA 600/4-75-004. Environmental Protection Agency, Research Triangle, Park, NC.

30. Deihl, B. J., 1984. Vertical Wind Direction Standard Deviation (σ_ϕ); Variation With Height and Comparison of Measurement Systems. Public Service Company of New Mexico, Albequerque, NM.

31. Wieringa, J., 1976. An Objective Exposure Correction Method for Average Wind Speeds Measured at a Sheltered Location. Quart. J. Roy. Meteorol. Soc., Vol. 102, pp.241-253.

32. Wieringa, J., 1980: Representativeness of Wind Observations at Airports. Bull. Amer. Meteor. Soc., Vol. 61, pp.962-971.

33. Irwin, J. S., T. M. Asbury, and W. B. Petersen, 1986. Description of the Savannah River Laboratory Meteorological Data Base for 1975 to 1979. U. S. Environmental Protection Agency, Research Triangle Park, NC.

34. Nieuwstadt, R. T. M., 1978. The Computation of the Friction Velocity u* and the Temperature Scale T* from Temperature and Wind Velocity Profiles by Least-Square Methods. Bound.-Layer Meteorol., Vol. 14, pp.235-246.

35. Irwin, J. S. and F. S. Binkowski, 1981. Estimation of the Monin-Obukhov Scaling Length using On-Site Instrumentation. Atmos. Environ., Vol. 15, pp.1091-1094. (Erratum, 1982, Atmos. Environ., 16, 887).

36. Holtslag, A. A. M., 1984. Estimates of Diabatic Wind Speed Profiles From Near Surface Weather Observations. Bound-Layer Meteor., Vol. 29, pp.225-250.

37. Pasquill, F., 1961. The Estimation of the Dispersion of Windborne Material, Meteorol. Mag., Vol. 90, pp.33-49.

38. Turner, D. B., 1964. A Diffusion Model for an Urban Area. J. Appl. Meteor., Vol. 3, pp.83-91.

39. List, R. J. 1966. Smithsonian Meteorological Tables, Sixth Revised Edition (Third Reprint). Smithsonian Institution, Washington, D. C.

40. Environmental Protection Agency, 1984. Calms Processor (CALMPRO) User's Guide. EPA-901/9-84-001. U. S. Environmental Protection Agency, Region I, Boston, MA.

41. Nappo, C. J. et al, 1982. The Workshop on the Representativeness of Meteorological Observations, June 1981, Boulder, CO. Bull. Amer. Meteor. Soc., Vol. 63, No. 7, pp.761-764. American Meteorological Society, Boston, MA.

42. Lockhart, T. J., 1985. Quality Assurance of Meteorological Measurements. In: Quality Assurance for Environmental Measurements, ASTM STP 867. J. K. Taylor and T. W. Stanley (eds). American Society for Testing and Materials, Philadelphia, PA.

43. Weiss, L. L., 1961. Relative Catches of Snow in Shielded and Unshielded Gauges at Different Wind Speeds. Monthly Weather Review, Vol. 89.

44. Environmental Protection Agency, 1976. Quality Assurance Handbook for Air Pollution Measurement Systems: Volume I - Principles. EPA 600/9-76-005. U. S. Environmental Protection Agency, Research Triangle Park, NC.

45. Kaimal, J. C., J. E. Gaynor, P. L. Finkelstein, M. E. Graves, and T. J. Lockhart, 1984. A Field Comparison of In-Situ Meteorological Sensors. BAO Report No. 6, NOAA/ERL Wave Propagation Laboratory, Boulder, CO.

46. Kaimal, J. C., J. E. Gaynor, and W. M. Baynton (Ed.), 1980. The Boulder Low-Level Intercomparison Experiment -- Preprint of WMO Report, BAO Report No. 2. NOAA/ERL Wave Propagation Laboratory, Boulder, CO.

47. Coulter, R. L., and T. J. Martin, 1987. Measurement of High Resolution Wind Profiles with a Minisodar. Sixth Symposium on Meteorological Observations and Instrumentation - Extended Abstracts, New Orleans, LA, January 12-16, 1987. American Meteorological Society, Boston, MA.

48. Underwood, K. H., 1981. SODAR Signal Processing Methods and the Riso-78 Experiment. PhD Thesis, Penn State University, State College, PA.

49. Tombach, I., R. Baxter, and R. Drake, 1983. Automatic Determination of Atmospheric Mixing Depth and Inversion Heights: Phase I. AV-FR-83/536. Aerovironment Corporation, Pasadena, CA.

50. Kristensen, L. and J. E. Gaynor, 1986. Errors in Second Moments Estimated from Monostatic Doppler Sodar Winds. Part I: Theoretical Description. J. Atmos. Oceanic Tech., Vol. 3, pp.523-528.

51. Gaynor, J. E. and L. Kristensen, 1986. Errors in Second Moments Estimated from Monostatic Doppler Sodar Winds. Part II: Application to Field Measurements. J. Atmos. Oceanic Tech., Vol. 3, pp.529-534.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-450/4-87-013	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE On-site Meteorological Program Guidance for Regulatory Modeling Applications		5. REPORT DATE June 1987
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Office of Air Quality Planning and Standards U.S. Environmental Protection Agency Research Triangle Park, NC 27711		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS		13. TYPE OF REPORT AND PERIOD COVERED
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

This document provides EPA's guidance on the collection and use of on-site meteorological data for regulatory modeling applications. It will form the basis for the regulatory review of proposed meteorological monitoring plans by the EPA Regional Offices and States. The document contains comprehensive and detailed guidance for on-site meteorological measurement programs, covering initial design and siting of a system, through data recording and processing, up to air quality model input.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Atmospheric Models Meteorological Instrumentation Meteorological Monitoring Meteorology		13B

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* None	21. NO. OF PAGES 192
	20. SECURITY CLASS *(This page)* None	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

DATE DUE