United States
Environmental Protection
Agency

Environmental Monitoring Systems
Laboratory
Research Triangle Park NC 27711

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Quality Assurance Handbook for Air Pollution Measurement Systems:

Volume IV. Meteorological Measurements

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Quality Assurance Handbook for Air Pollution Measurement Systems:

Volume IV. Meteorological Measurements

Peter L. Finkelstein, Daniel A. Mazzarella, Thomas J. Lockhart, William J. King, and Joseph H. White

Notice

Peter L. Finkelstein is a physical scientist in the Environmental Monitoring Systems Laboratory. He is on assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce

Foreword

Measurement and monitoring research efforts are designed to anticipate potential environmental problems, to support regulatory actions by developing an in-depth understanding of the nature and processes that impact health and the ecology, to provide innovative means of monitoring compliance with regulations and to evaluate the effectiveness of health and environmental protection efforts through the monitoring of long-term trends. The Environmental Monitoring Systems Laboratory, Research Triangle Park, North Carolina, has the responsibility for assessment of environmental monitoring technology and systems; implementation of agency-wide quality assurance programs for air pollution measurement systems; and supplying technical support to other groups in the Agency including the Office of Air, Noise and Radiation, the Office of Toxic Substances and the Office of Enforcement.

This document was developed to help fulfill the need for a quality assurance manual for meteorological measurements that are frequently made in conjunction with air quality studies. A quality control and assurance program is a necessary part of any environmental measurement system. Meteorological measurements are made in conjunction with pollutant dispersion studies, model validation studies and legally mandated air pollution monitoring activities. This manual will guide and assist in the development of specific quality assurance plans for those meteorological measurement programs.

Thomas R Hauser
Director
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Abstract

There is little information available on suggested quality assurance procedures to be used with the collection of meteorological data. This manual is an attempt to fill a small part of that gap by suggesting QA procedures that can be used with meteorological measurement programs designed to supplement air quality studies.

This manual is organized in three main sections. The first discusses the measurement process for each meteorological variable from the perspective of quality assurance. This includes general guidance and suggestions for judging the adequacy of the process of selection of the measurement system (procurement specifications and receiving inspections against the specifications), installation, documentation of the initial system calibration, and the ongoing operating procedures (calibration, preventive maintenance, repair and routine inspection. The result of this first section is a method for estimating the accuracy and precision of the measurement process. The second section gives guidance on the proper siting of the various meteorological sensors to be compatible with the intended application of the data. Where possible, this guidance follows that of the World Meteorological Organization (WMO, 1971) although some changes are made because it is recognized that the goals of WMO's climatological program may not be the same as those of an air pollution control agency. The final section reviews various approaches to data validation and makes some recommendations for a program that may be suitable for the needs and resources of an air quality study.

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Section 1.0
Introduction

Most air pollution control agencies have been measuring meteorological variables for as long as they have been measuring atmospheric contaminants. Wind speed, direction, and temperature are the usual measurements. For the most part, these data have been filed away and forgotten, to be retrieved occasionally to help track down the source of a noxious odor, for use in air pollution episodes, or the accidental spill of a toxic chemical.

Serious attempts to use the monitored meteorological information to help analyze air quality data or as input into a diffusion model are usually met with limited success Upon inquiry into the status or quality of the data, one is frequently told such things as "Oh, that station used to be O K., but since we put it up in 1964 some trees have grown up around it," or "Well, you can have that data if you want, but we don't know if it is any good—the propeller is still spinning so I suppose it's O K." With uncertainties such as these, it is no wonder that the diffusion meteorologist turns so often to the nearest National Weather Service office for data This is not meant as criticism of any air pollution control agency For the most part, these agencies have been understaffed, underfunded, and overworked Meteorological data have had a uniquely low spot on priority lists, if they were thought about at all Federal agencies have also been lax in setting good examples of how to run meteorological quality assurance programs

Recent events, however, have combined to bring about a needed change in this situation Increased emphasis on models for decision-making has highlighted the need for better urban-scale meteorological data Photochemical models, especially, have a need for a dense network of meteorological monitoring stations. Agencies have rapidly come to realize that they have a need for the meteorological data they have been gathering all along In addition, the recently published "Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD)" (USEPA, 1980) document requires new sources to monitor meteorological and atmospheric variables at many proposed sites for new industrial facilities in order to evaluate their air quality impact Finally, a committee of the American Meteorological Society (Hanna, 1977) has recommended that dispersion parameters used in models should be measured directly on site rather than continue use of standard values from tables as has been done in the past.

In response to this growing interest in and need for higher quality meteorological data, various air quality monitoring groups have perceived the need for a formal quality assurance plan for the collection of meteorological data. This report addresses this need by suggesting a quality assurance program that will be useful for meteorological monitoring done in support of air pollution studies It is hoped that such a program would benefit short- and long-term field measurement programs Others in the meteorological monitoring business may also find it useful in the development of their own quality assurance programs

1.1 Organization

This report is organized in three main parts Section 2 discusses the meteorological measurement system. It reviews methods of measurement, procurement, maintenance and calibration from the perspective of quality assurance (QA). The practical advice comes principally from experience of the authors. The QA procedures follow the principles of the EPA Quality Assurance Handbook (USEPA, 1976).

Section 3 provides guidance for judging the suitability of the siting of the various meteorological sensors Where possible this guidance follows that of the World Meteorological Organization (WMO, 1971) although some changes are made since it is recognized that the goals of WMO's climatological program may not be the same as those of an air pollution control agency

The final section (Section 4) reviews various approaches to data validation procedures and makes some recommendations for one example program Both automatic and manual validation procedures are discussed. A mixture of both is suggested, but each monitoring group will have to evaluate its own situation before designing its procedures

1.2 Implementation

Before implementing a quality assurance program, an agency should try to evaluate the projected uses of the data it is gathering and the value of that data or, conversely, the cost of invalid data. This exercise should help in the budget decisions connected with the QA program.

As with any other new program, the implementation of a quality assurance program in a laboratory that did not previously have one will require an additional expenditure of resources. The adoption of a program on paper, without allowing for the additional manpower and money that are needed, will not result in substantial improvement in data quality. The challenge is to develop a program that meets an agency's data needs and is cost-effective. This manual has been prepared to assist in achieving that goal.

Section 2.0
Quality Assurance of the Measurement Process

All too often the meteorological system is considered an infallible instrument or group of instruments that, once installed, yields accurate measurements until catastrophic failure, an easily recognized event, occurs. This is not true. Meteorological instrumentation requires calibration, preventive maintenance, and constant checking if the data acquired are to be accurate and complete

This section provides guidelines for proper meteorological instrument operation to obtain good quality data. The variables discussed here are: wind speed, wind direction, temperature, humidity/dew point, precipitation, and total sky radiation.

For each instrument, selection and acceptance criteria (procurement), lab and field calibration procedures, recommended maintenance procedures, and audit procedures are presented

Recommendations for the implementation and management of a quality *assurance (QA) program for meteoro*logical instrumentation are presented

2.1 Quality Assurance Program for Meteorological Measurements

Quality assurance (QA) applied to environmental monitoring consists of both "the system of activities to provide a quality product" (traditional quality control) and "the system of activities to provide assurance that the quality control system is performing adequately" (traditional quality assurance) The first of these quality control (QC) functions consists of those activities performed by station operators directly on the instruments, e g , preventive maintenance, calibrations, etc. These activities are described for each of the individual instruments in Sections 2 3 through 2 8. The purpose of the second set of activities is to manage the quality of the data and administer corrective actions as necessary to ensure that the data quality requirements are met. This section describes the planning, operation, and reporting of the quality assurance effort

2.1.1 *Planning for a Quality Assurance Program*

A formal quality assurance program should be designed into the monitoring system so that provisions may be made in the system design for desired quality control checks and for better monitoring of system operations. If these activities are planned and provided for by incorporation of necessary readouts, calibration sources, etc., then they are more likely to be performed in a satisfactory manner

The quality assurance activities necessary for a monitoring program are determined by the program data quality requirements which are, in turn, determined by the purpose for which the data are to be used. Consideration must also be given to possible future applications of the data.

The formal plans for quality assurance must be presented in a document called the QA Plan *This document lists all* necessary quality-related procedures and the frequency with which they should be performed. Specific information to be included is described below:

Project personnel responsibilities: Responsibilities of personnel performing tasks that affect data quality

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

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

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

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

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

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

More details on the requirements for a QA plan which is to be submitted to EPA are available in "Interim Guidelines and Specifications for Preparing Quality Assurance Project Plans," prepared by the Office of Monitoring Systems and Quality Assurance (1980).

2.1.2 *Operation and Management of a Quality Assurance Program*

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

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

The audits—both performance and system—provide the manager with the best information for the quantitative and qualitative assessment of the status of the QA program The following sections present considerations for the performance of audits and evaluation of results

2.1.2.1 Systems and Performance Audits-Systems and performance audits should be the most quantitative and unbiased measures of data quality available to the QA coordinator The systems audit is an inspection of monitoring stations for indications of proper quality control procedures and adequacy of the instrumentation for making the desired measurement

Inspections are made to determine

- adequacy of recordkeeping
- level of preventive maintenance
- suitability of equipment used for calibration and operational checks
- adequacy of operating procedures

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

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

Performance audits provide a quantitative indication of the accuracy of measurements being made by the physical verification of the instrument calibration. Suggested audit methods are described for each of the variables in Sections 2 3 through 2.8 and summarized in Table 2 1 1 Having independent investigators execute the audit applies also to performance audits

2.1.2.2 Interpretation of Audit Results-The interpretation of audit results for meteorological instrumentation will necessarily be somewhat different from interpretation for ambient air monitoring instruments because of differences in the audit techniques Air monitoring equipment is accessible because it is usually installed in air conditioned shelters with the sample drawn into the instrument through a tube Calibrations or audits are performed by generating known concentrations of the monitored gas in a manifold and letting the instrument draw its sample from that manifold in the same manner in which it would draw the ambient air sample. The test conditions, therefore, accurately simulate the measured conditions with the measured quantity being carefully controlled

Meteorological instrumentation, however, usually consists of a sensing element that must be located directly in the field being measured without altering that field. Producing a known field of meteorological variables at the monitoring site is exceedingly difficult, if not impossible. Once installed, the instrument may only be checked by generating an artificial field (e.g , spinning anemometer cups with a motor, orienting the wind vane toward aiming stakes, or submersion of a temperature sensor in a bath) Checks made in this manner do not detect or quantify coupling errors that occur at the sensor/air interface (slippage of cups in wind because of increased bearing friction, errors in indicated direction due to geometrical asymmetry of the vane, or effects of radiation on temperature measurements). The checks represent only a calibration of a portion of the system and, consequently, may *not be routinely used to evaluate* accuracy on the entire measurement system.

The instrument may also be checked by the technique of collocated sensors, in which the audit sensor is subject to the same air/sensor interface errors as the audited sensor. When audits of this type are conducted, the ambient field as measured by the audit device is assumed

Table 2.1.1. *Summary of Performance Audit Methods for Common Meteorological Monitoring Instruments in the Field*

	Audit method		
Variable	*Collocated transfer standard*	*Measurement system audit or calibration*	*Operational check*
Wind speed	*Anemometer with calibration related to NBS*	*Known rate of rotations driving sensor shaft. Starting torque measurement for threshold*	*Substitute known frequency or voltage*
Wind direction	*Wind vane with independent orientation*	*Alignment to orientation target and rotate in three or more known angular steps*	*Substitute known resistance for potentiometer type*
Sigma theta	*Calculate from direction samples*	*Calculate from direction samples*	*Substitute known amplitude and wave shape in frequency window*
Temperature	*Thermometer with calibration related to NBS in acceptable aspirated radiation shield*	*Compare with transfer standard at two or more temperatures in stable thermal masses For differential temperature test zero difference at two temperatures*	*Substitute resistance or voltage for sensors*
Humidity	*Assmann psychrometer, cooled-mirror dewpointer*	*No practical field method. Return for lab calibration*	*Substitute resistance for temperature*
Solar radiation	*Calibrated pyranometer*	*Cover sensor for zero point. Return for lab calibration*	*Substitute millivolts or microvolts for sensor*
Precipitation	*Not applicable*	*Introduce known volume of water at rate about 1 inch/hour into known inlet area (tipping bucket) Use calibration weights (weighing gage)*	*Substitute event simulator (tipping bucket) or resistance (electric weighing gage)*

Table 2.1.2. Recommended Tolerance Limits for Audit Results

Variable[1]	*Calibration via artificial field**	*Collocated sensors***
Wind speed	*±0 2 m/s*	*±0 5 m/s*
Wind direction	*±2°*	*±5°*
Temperature	*±0 25°C*	*±0 5°C*
Temperature difference	*±0 1°C*	*±0 2°C*
Humidity/dew point	*Return to manufacturer†*	*±1.5°C****
Total sky radiation	*Return to manufacturer†*	*±5% Full scale (70 W/m²)*
Precipitation	*±.01"*	*±10% of reading*

**Artificial field implies the simulation of the measured variable by artificial means (e.g., spinning anemometer cups by controlled speed motor).*

***Sensors utilizing the same measurement technique operated in similar housings located adjacent to the audited sensor*

****Dependent on measurement technique; - some methods may be better.*

†Or an impartial standards laboratory. See "A Directory of Standards Laboratories" by National Conference of Standards Laboratories, NBS, Boulder, CO 80303

[1] 10- to 20-minute averaging time when averaging is required.

to be the known field. Care must be taken when this method is used for calibration or audit purposes because the characteristics of the atmosphere are not controlled and unknown spatial and temporal variations may exist

The audit data indicate the state of instrument calibration because most audit procedures verify the total system except for the air/sensor interface It is possible for a system to receive a good audit report and still make poor measurements of meteorological conditions because of problems at the air/sensor interface or due to poor siting. However, this is not likely if good sensors are used and proper siting precautions are taken. To further minimize the chances of inaccurate measurements going unnoticed, performance audits should always be accompanied by inspections for potential problems that might cause the measured values to be unrepresentative of ambient conditions.

The calibration errors indicated by a performance audit should fall within the limits specified in the QA Plan Table 2 1 2 lists suggested tolerance levels for each of the measurement techniques Exact limits should be determined by monitoring program requirements Any audit results falling outside these limits indicate a problem that should be rectified by normal maintenance procedures and followed by reauditing of the system. The audits are only checks and should not be used to determine calibration equation coefficients for the instrument or for other types of data correction or adjustment.

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

Manual examination of audit vs sample data for differences within acceptance limits.* Either instantaneous values or average values over the period of audit may be compared. Also, if a collocated test were run over a period sufficiently long that widely varying levels of the measured variable were encountered, then results of a regression between the audit and sample values will yield difference and bias information

Statistical evaluation of audit results either from audits performed on multiple stations or multiple audits on a single station. Simple tests are described in the *QA Handbook,* Vol I, Section G, which detect bias in system measurements through audit data taken over a network These tests include the sign test and the paired t test More complex tests are available

2.1.3 *Quality Assurance Program Reports*

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

- results of performance audits
- results of systems audits
- percentage of data reported
- cost of QA effort
- problems that degrade data quality and corrective action taken

*Note that acceptance limits consider not only the variations expected in the measurement system but also variations in the audit measurement system

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

2.2 Quality Assurance Considerations Common to All Variables

Two areas common to all systems must be considered One is procedural including procurement specifications, acceptance testing, recordkeeping and reporting The other is related to the hardware of the system including power supplies, recording systems, multiplexers, operating power source, and some cables

The amount of the contributions to the error of the common hardware parts of a measurement system depend on the type of system If the system is a digital logging system where voltages are provided by the signal conditioners of each sensor to a common multiplexer, analog to digital (A to D) converter and digital recorder, the contribution of the system to the error budget of the measurement is usually small A good quality A to D converter will be accurate to 0 1 percent of full scale. Once converted, the digital handling should be error free except for the last digit uncertainty If the resolution of the digital data is also 0.1 percent of full scale or the least significant digit is properly rounded from such a resolution, the contribution to the measurement error is less than 0.2 percent Rounding in digital systems can cause an unacceptable bias when it is not done correctly This is easily checked by looking at a frequency distribution of real data at the resolution of the recorded data. When auditing a system with a collocated transfer standard where synchronous measurement differences are examined, it is important to restrict the differences to those caused by the *measurement* system To find any detectable bias from rounding, filtering or averaging which might be unexpected, examine the shape of the frequency distribution (not cumulative) for reasonableness. Other tests designed to challenge these functions of a digital data system may also be used. It is most important for the auditor of a digital system to be satisfied that the system works without bias by whatever method might be appropriate

When the common part of the system is something like a multipoint recorder or a series of single-channel chart recorders, the error from the recording system may be as large or larger than the error from the rest of the measurement system for the variable This error is tolerable if it is a backup recording. If it is the primary data source, recording error may be a serious problem; particularly if the application requires a high degree of accuracy.

The quality control effort common to all variables must be documented from observations taken directly from the charts and logs maintained by the station operators and their supervisors The following reports should be kept for the purpose of efficient station operation, and they can be a useful source for any good QA plan

- *Calibration Log.* The calibration log contains detailed calibration information including date and time, name of person calibrating, calibration technique used, problems noted, sensor adjustments made, and calibration values and sensor responses (before and after adjustments)
- *Operational Log.* The operational log contains records of activities performed on the meteorological measuring system including preventive maintenance, repairs, inspections, and special test data not recorded elsewhere. Some test parameters should be maintained in the operational log on a regular basis to provide baseline information on proper operating conditions of the instrumentation. This information can be invaluable in troubleshooting once problems are noted by providing nominal operating values and the amount of expected variation in those values. Examples of data that should be recorded are readings associated with any test positions on the instrument, bridge excitation voltage (if accessible), and line voltage.

Not all quality assurance recording functions performed by the station operator are strictly for the purpose of furnishing information to management. Some of the recordkeeping functions enable the station operator to spot indications of potential problems before data are lost, e g., the routine recording of operational values described above. Some data are subject to day-to-day variations and it is difficult to evaluate if individual values are within acceptable limits Data of this nature are best recorded and plotted using control charts Typical control charts include response to zero/span checks and digital versus strip chart readings

2.2.1 *Instrument Procurement*

The function of QA in the procurement process is to verify the presence in purchase orders or contracts of performance specifications in unambiguous terms along with some indications of how verification tests will be conducted The importance of this function is directly proportional to the importance of the instrument having the specified characteristics

In choosing any meteorological instrument or array of instruments, the potential user should carefully evaluate his needs for data Data requirements should be identified and a list made of suitable instrument configurations that meet these requirements For most air pollution monitoring applications, meteorological instrument systems will be commercial, off-the-shelf items. The suitability of each instrument to perform in the anticipated field environment is evaluated by examining such characteristics as stability, linearity, response time, and durability

Budget considerations may appear to eliminate certain candidates but should be carefully examined Purchasing a meteorological instrument is more than a simple capital equipment outlay A scientific instrument requires a certain amount of attention Man-hours invested in data reduction, preventive maintenance, calibration and repair, and the value of lost data are real budget considerations Maintenance records of candidate instruments should be checked because the time a component spends in the manufacturer's service department represents wasted resources and lost data. Generally it is best to purchase components from one manufacturer Although it is possible to obtain sensors, bridge circuitry, housings and mounting apparatus from different sources, purchasing in this way splits responsibility, invites problems of component mismatching, and frequently results in delays. As a rule of thumb, a delivery schedule of approximately 3 months is reasonable for most meteorological instrumentation; 4 months is average.

2.2.2 *Acceptance Testing*

Never assume that the manufacturer has sent a complete, working instrument. Since warranties may expire in as short a period as 90 days, the instrument should be examined upon receipt, particularly if it is not slated for immediate deployment. Any damage to the shipping carton should be documented with the shipper The instrument should then be unpacked and assembled according to the manufacturer's written instructions. Each component should be inspected for physical damage Open access plates and inspect for loose connections and other visible effects All cables should be checked for continuity Bench test the instrument under controlled conditions Using the operations and maintenance manuals, check as many performance specifications as possible. Document all acceptance testing and bring problems to the attention of the supplier or manufacturer immediately

When an important performance characteristic is specified, it is prudent to verify that performance with an acceptance test. If it is a design feature (like overshoot or damping ratio on a wind vane), it can usually be verified by a test on a randomly selected sample of the units purchased. The cost of this type of documentation should be considered as a part of the cost of specification. If verification acceptance testing is not planned or budgeted, it should be understood that the specification becomes an expression of desire or expectation and it should be used to describe the data collected only with a footnote to qualify it as a manufacturer's claim or by reference to tests by others on the same kind of instrument

2.2.3 *Calibrations*

The calibration of the part of the system common to all variables is usually a simple task and should be done initially in conjunction with the acceptance inspection and testing It may require simply challenging the recording system with a voltage or current within the operating range and verifying that the output is within the accuracy specification. If the recording subsystem does not have a specific specification, these test results will define it Of course, it must be smaller than the total measurement accuracy specification

After this initial test, it is often unnecessary to repeat the test or calibration except in cases where repairs or replacements are involved. That part of the system common to all variables is usually included in the total system calibration or audit done for each variable and need not be considered as an independent subsystem.

2.2.4 *Audits*

The audit is an integral part of the quality assurance program for any field measurement exercise. To minimize bias, audits are usually performed by an independent investigator not administratively connected with the organization conducting the measurement program. The audit is similar in some respects to a field calibration check in that a major objective is to determine if the measurement system has retained its calibration. During an audit, however, no changes are ever made to the instrument or to the calibration coefficients.

The system audit is common to all variables and is described in Section 2.1.2. It involves an examination of all site logs and a review of instrument siting and installation, daily operating procedures, preventive maintenance (PM) activities, and calibration methods. A systems audit should be scheduled near the beginning of a measurement program.

The performance audit is specific to each variable and is discussed with each variable in the following paragraphs of this section.

2.2.5 *Operational Checks and Preventive Maintenance*

To ensure the highest possible data quality, the user should establish a preventive maintenance routine and perform operational checks daily or as often as the site is visited. Except under extremely unusual circumstances, no piece of meteorological equipment should go unattended for more than 30 days. Some instruments, such as pyranometers, require daily attention to assure data quality. Operational checks include timing checks and adjustments, servicing the recorder needs, logging activities and observations, and cursory inspection of data for anomalous behavior. Preventive maintenance (PM) involves specified routine activities such as cleaning, tightening, lubricating, and scheduled replacing of minor parts. The user should maintain a log of all PM and operations checks.

2.2.6 *Preparation for Field Installation*

Certain routine preparation is required before a meteorological sensor system is deployed. If the instrument is not newly purchased and has not recently been operating, it should be checked following the basic procedure used for acceptance testing (paragraph 2.2.2). The checkout is followed by bench calibration, after which it is desirable to set up the instrument in field configuration near the main laboratory for a shakedown period. If several instruments are involved, side-by-side comparisons can be made, strengthening the quality assurance program. The shakedown period may vary in length but should at least verify that the instrument is in good working order. Following shakedown, the system is dismantled and carefully packed for shipment to the field. A physical damage inspection should be made at the destination.

2.3 Wind Measurements

2.3.1 *System Description*

Wind measurements are of primary importance in studies of the diffusion and transport of atmospheric pollutants. These measurements include wind speed, wind direction, and turbulence or gustiness.

There are many wind-measuring systems commercially available. Some are ruggedly constructed, designed for a wide range of applications, and require minimum attention. The more delicate instruments, such as those used for measuring small-scale turbulence, can only be used during selected periods of favorable weather.

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

Anemometers - A number of wind speed sensors operating on a variety of physical principles are available commercially. However, the rotational cup and propeller anemometers are the most commonly employed wind speed sensors. The more esoteric designs are generally used in very specialized studies.

Wind Vanes - Wind-direction-measuring sensors are operated by wind exerting pressure on a surface that rotates about a fulcrum. The standard vane measures only the horizontal wind direction, but the bidirectional vane is free to move through 360 degrees horizontally as well as ±50 degrees or more from the horizontal. The shape and design of the vane surface may vary with the manufacturer (Figure 2.3.1).

Combination Wind Sensors - Two types of sensors incorporate both

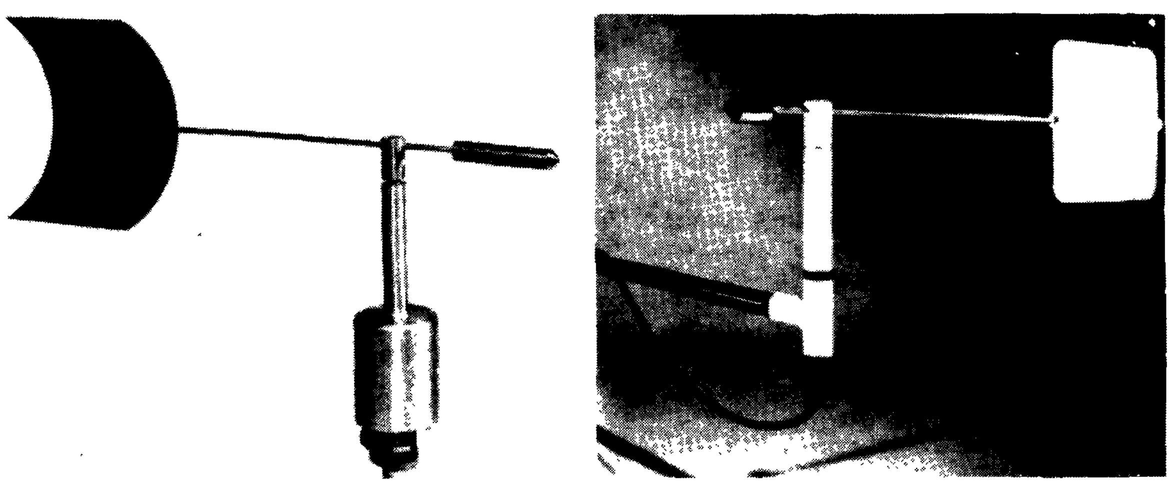

Figure 2.3.1. *Typical wind vanes by Climet Instruments, Inc., (left) and R. M. Young Company (right).*

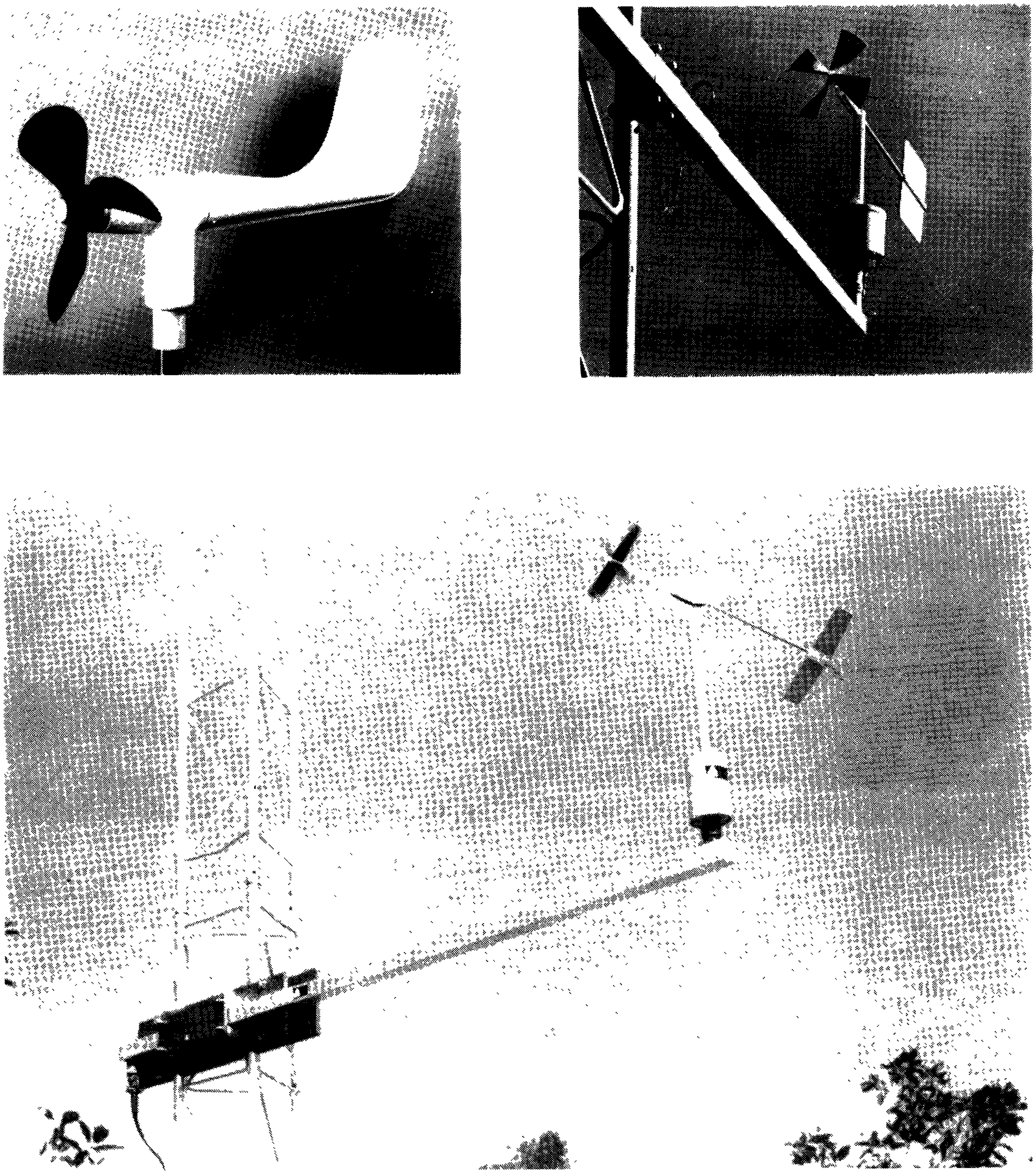

Figure 2.3.2. *Propeller wind vanes by Bendix Friez Instrument Division (upper left), by R. M. Young Company (upper right) and by Meteorology Research, Inc. (lower).*

direction and speed measuring capability in a single mechanical device. The propeller vane sensor measures two-dimensional flow (Figure 2.3.2), and the propeller bivane sensor measures three-dimensional flow.

Wind component anemometers can be used to determine the wind speed and direction(s), using simple trigonometry. These instruments include the x,y,z prop (often called u, v,w), the sonic, the vortex shedding, and the ion flow anemometers (see Table 2.3 1).

Transducers - Transducers convert the weather element measured by a sensor into an electrical or recordable signal. This discussion will be limited to transducers used in rotation-type wind speed sensors and vane-type direction sensors.

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

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

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

Readout Devices - Readout devices are classified as mechanical or electrical. Few of the mechanical, drum or disc drive recorders are now used for recording wind. Electrical recorders are (1) galvanometric, direct-writing, strip-chart type, (2) null-balance, servo-operated, (may be potentiometric), DC bridge, or force-balance servo type; (3) event or operations; (4) digital; and (5) other special types

Direct writing (D'Arsonnal movement) galvanometric recorders with strip charts are used most frequently for wind measurements They are used because of their reliability and their speed of response. The chart drive mechanisms are available as hand wound, spring driven, battery powered, or AC powered It is important to select a recorder in which the damping characteristics of the galvanometer do not degrade the response of the sensor and are in compliance with the frequency response required in the study

Most galvanometric recorders used for wind measurements are continuous curve-tracing recorders The *chopper-bar* type, designed to make an imprint on pressure-sensitive paper each time the meter pointer is clamped against a sharp-edged platen, produces a record that is noncontinuous. Imprints are usually made every 2 seconds, so in rapidly varying winds the record appears very scattered Some manufacturers of meteorological instruments supply a recorder with a built-in signal conditioner, that reduces the scatter through the use of either unspecified or selective time constants on the response of the galvanometer This conditioner must be viewed critically if calculation of the standard deviation of the measurement is an objective in analyzing the record

Potentiometric recorders, used frequently for wind measurement, may not have the rapid response characteristics of galvanometric recorders As a null-balance device, the input impedance is

Table 2.3.1. *Types of Anemometers and Their Operating Principles*

Physical principle	*Anemometer type*	*Measurement*
Rotation	*Vane-oriented propeller*	*Horizontal speed*
	Bivane-oriented propeller	*Total speed*
	Fixed propellers	*Three-dimensional components on perpendicular axes*
	Cups	*Horizontal speed*
Pressure	*Plate*	*Horizontal speed*
	Tube	*Horizontal speed*
	Bridled cups	*Horizontal speed*
Cooling	*Hot wire*	*Directional flow components*
	Hot thermopile	*Directional flow components*
	Hot film	*Directional flow components*
Sound	*Sonic*	*Directional flow components*
Vortex shedding	*Vane-oriented shape*	*Horizontal speed*
Ion flow	*Transport*	*Horizontal speed*

very high when the stylus is at equilibrium, therefore errors due to electrical loading of the sensor output and errors due to voltage drops in long signal leads are minimized.

Multipoint potentiometric recorders, which sequence through a series of inputs or scheduled cycles, have no value in recording wind. Instantaneous samples of wind direction or wind speed once every few minutes are useless in most air pollution investigations. Curve-tracing potentiometric recorders are useful, and are available with charts that require ink or with inkless charts that operate with a heated stylus.

Digital systems are becoming more popular for logging and displaying wind data. They come in a wide range of designs and are usually elaborate systems that include analog to digital conversion, integration over specified intervals, and memory or storage capability. The output format of these systems should be compatible with the computer used for data processing.

2.3.1.1 Wind Sensor Characteristics-Cup anemometers, propeller anemometers, and wind vanes continue to be the best sensors for measuring wind speed and determining wind direction over a broad range of applications. Other types of sensors have unique characteristics for special projects or research This discussion is limited to the characteristics of devices used most frequently in operational programs.

Cup anemometers are complex shapes where the net torque (lift greater than drag) causes a rate of rotation roughly proportional to wind speed They respond to any horizontal wind direction which is an advantage but they are also responsive to the vertical component of the wind. In turbulent flow, the output (average speed) may be closer to the total speed than to the presumed horizontal component (MacCready, 1966).

The design of the anemometer cup assembly and the material from which it is constructed are important in determining durability, linearity, starting threshold, and dynamic response of the instrument. Three conical cups give better performance than hemispherical cups (Figure 2.3 3) and are preferred over the older four-cup design The ratio between cup diameter and cup wheel diameter influences the calibration curve (Gill, 1973) Starting threshold is defined as the lowest wind speed at which the rotating cups meet the accuracy specification (Lockhart, 1970)

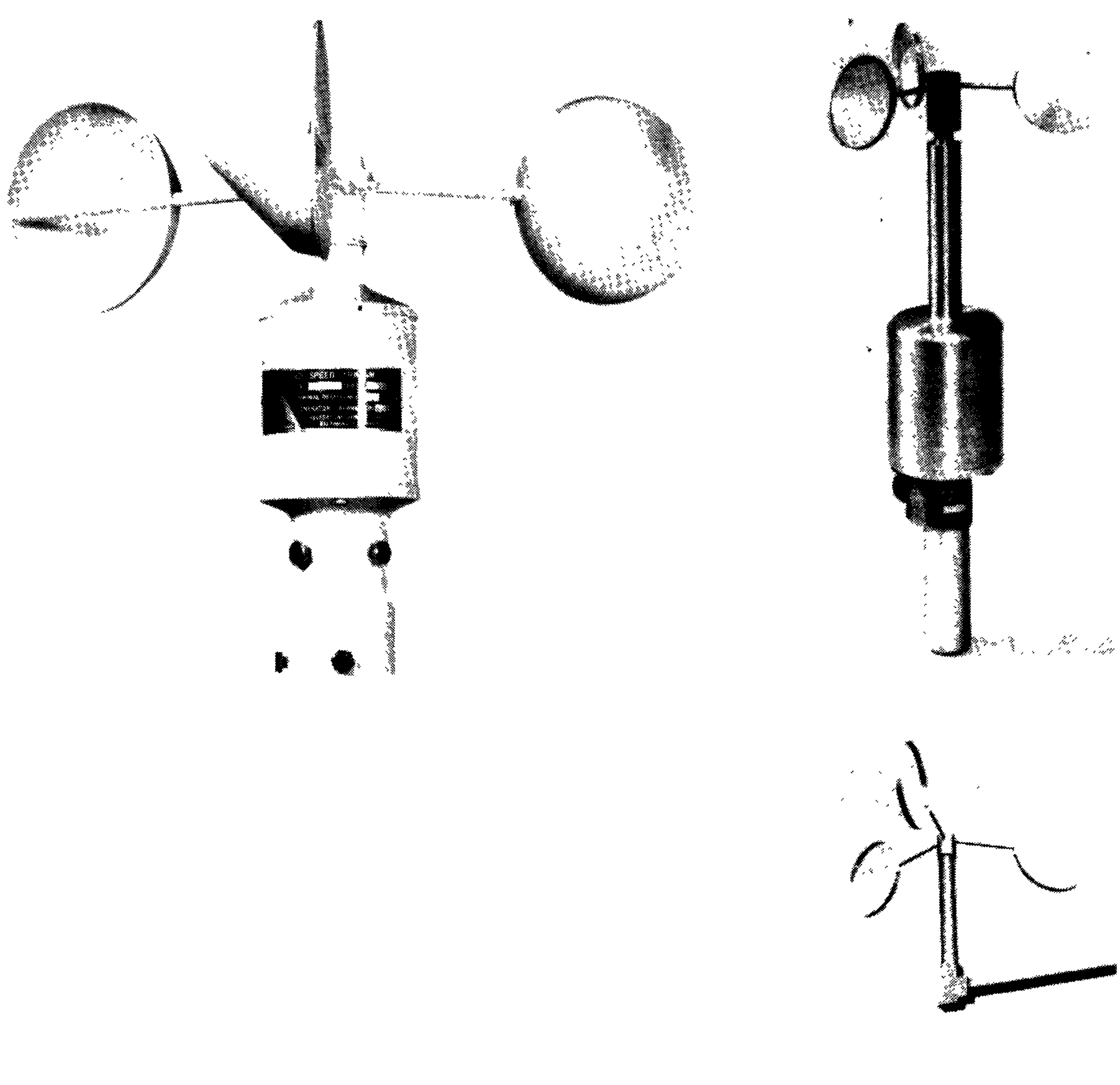

Figure 2.3.3. *Typical three-cup anemometers featuring conical cups. Manufacturers are Belfort Instrument Company (upper left), Climet Instruments, Inc. (upper right) and C. W. Thornthwaite Associates (lower).*

In order to define the smallest eddy size to which cups will be responsive, a dynamic characteristic known as the distance constant must be known. This is determined in a wind tunnel by measuring the time for the cups to reach 63 percent of the tunnel speed after being released from a nonrotating condition. The distance constant in meters may be expressed as a time constant in seconds at a given wind speed by dividing by that wind speed in meters per second.

Propeller anemometers, especially helicoid types, are primary sensors with rotation rates linearly proportional to the wind speed over a wide speed range (Gill, 1973). Propeller anemometers must be oriented into the wind. The error from the failure of the vane to perfectly orient the propeller is small since propellers have a nearly cosine response; i.e., the propeller turns at a rate almost directly proportional to the wind component parallel to its axis. Like the cup anemometer, the propeller anemometer is a first-order, nonoscillatory system whose dynamic characteristics can be described by the distance constant referenced above.

Fixed axis propeller anemometers are designed to measure two or three components of wind simultaneously at a point in space They represent a special type of propeller anemometer for the direct measurement of turbulence (Gill, 1975). Three helicoid anemometers in an orthogonal array measure the wind for the axes U-V-W. Each propeller turns at a rate almost proportional to the wind component parallel to its axis. Cosine response, although not yet perfected, is critical in this equipment; but this device does not have the static balance limitations of the bivane (a two axis wind vane), which is also used for turbulence measurements. Under conditions of rain, snow, and heavy dew, the bivane imbalance may produce unacceptable errors.

Wind vanes have a damped and oscillatory motion. This characteristic second-order response is the result of such factors as weight of materials, shape and size of vane, and location and weight of counter-balance. One indication of the performance of a vane is the starting threshold. As described by Finkelstein (1981), this is the lowest speed at which a vane released from a position 10 degrees off the centerline in a wind tunnel moves to within 5 degrees of center

There are several dynamic characteristics, identifiable as constants, that can be used to define the performance of a wind vane (MacCready, 1965, and Wieringa, 1967) in response to a step function. These include damping ratio, damped wavelength, undamped wavelength, and delay distance. Undamped wavelength is used in determining the dynamic response of a wind vane to sinusoidal wind direction fluctuations.

Damping ratio is a constant that is dimensionless and independent of wind speed. It is calculated from the relative amount of overshoot on each of two successive half cycles of a decaying oscillation If the ratio of two successive swings is designated as Ω, then the damping ratio ζ is calculated from the equation:

$$\zeta = \frac{\ln \frac{1}{\Omega}}{\sqrt{\pi^2 + \left(\ln \frac{1}{\Omega}\right)^2}}$$

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

The *damped wavelength* is easily determined by multiplying the time for one complete oscillation by the wind speed in a tunnel

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

2.3.1.2 Wind Data Requirements-Any data requirement should be expressed in the context of all applications for which the data may be used. Wind data are used in environmental monitoring for source location, transport and dilution modeling and as a diffusivity indicator. The principal specifications are dynamic range (most important is the threshold) and dynamic performance (distance constant for speed and damping ratio and delay distance for direction) It is also important to specify the averaging time and method in order to judge the adequacy of the measuring and recording system. For most atmospheric dispersion studies, a starting speed of 0.5 m/s or less is appropriate for both vanes and anemometers. Wind vanes should have a damping ratio of 0 4 or greater and a delay distance of 5 m or less. Anemometers should have a distance constant of 5 m or less. For climatological studies, less sensitive instruments may be used.

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

2.3.2 *Procurement*

In purchasing a wind measuring system, follow the general guidelines advanced in Section 2.2.1, "Instrument Procurement." It might be possible in research projects to spend more for instruments with the best specifications, or instruments of most recent design; but in operational programs, only the field-tested and time-proven instruments with known performance records should be purchased.

Caution should be used in purchasing components as opposed to systems, especially if the procurement of wind equipment is part of an installation involving other instruments. It is important to match the dynamic characteristics of the wind sensors, and to match the electrical characteristics of the transducers with the readout device. The omission of such a minor consideration as mounting hardware could delay completion of an installation. In digital systems, special attention should be given to sampling and averaging times as well as to instantaneous as opposed to integrated values.

2.3.3 *Acceptance Testing*

Follow the general guidelines set forth in Section 2.2 2, "Acceptance Testing " Be certain that the supplier has provided all calibration certification data, including curves and specifications. Be particularly sure that there is provided a table or formula relating rate of rotation of the anemometer shaft (or frequency for light-chopper sensors if the number of pulses per revolution is also given) to wind speed (or output voltage given a voltage to speed range relationship). This will usually relate to a nominal propeller or cup. The specific propeller or cup assembly should have a permanent identification code (serial number). In those cases when wind tunnel calibration data are provided, this identification is required.

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

360 degrees and 001 degrees performs as specified

2.3.4 *Calibration*

Refer to the general notes in Section 2.2 3, "Calibrations."

Bench Calibrations - Specific dynamic response characteristics such as threshold speeds, damping ratios, delay distances and distance constants can only be checked in a wind tunnel. Instruments should be returned to the manufacturer or a properly equipped wind tunnel facility for major calibration

The system manual will generally have calibration methods specified For wind speed the usual signal conditioner will require a DC voltage input which represents some output value in volts *and* wind speed units or it will require a frequency to represent some output value in volts *and* wind speed Full scale is often used Sometimes the sensor is used in calibration by turning the shaft at a known rate of rotation Sometimes the system will have some level of built-in "calibration" which tests some parts of the system Use the manufacturer's method for bench calibration Other methods may also be used but they should supplement the manufacturer's instruction rather than replacing it, at least initially

For wind direction sensors with potentiometers the manufacturer may specify substitution of known resistance for various angles relative to the sensor housing Positioning of the connected sensor vane or built-in substitution resistance may also be specified. Use the method described by the manufacturer augmented by whatever additional tests will add useful information. These might include a measurement of the angular size of the "open space" where the potentiometer winding is left out to avoid shorting by the wiper, a measurement of hysteresis by approaching known positions from both clockwise and counterclockwise rotation, and testing any discontinuity avoiding operation (540 degree range types) Any adjustments, mechanical or electrical, must be in accordance with the manufacturer's instruction (either from the instrument manual or direct communication) to avoid damage or voiding the warranty

The common point of sensor deterioration is in the bearings of the bearing shaft assemblies of both the speed and direction sensors When bearings start to fail as they inevitably will do, the starting threshold will increase. The low wind speed data are most important for air quality applications because the initial dilution is small and the concentration therefore is high The deterioration of bearing performance is also hard to see in the data until the problem becomes quite serious. For example the data cannot discriminate (by usual inspection) between a system with an acceptable threshold of 0 5 m/s and one that has deteriorated to 0 7 m/s

There is a method by which the bearing condition can be measured (Lockhart, 1978). The use of an instrument called a torque watch is not new but it is not widely applied as yet It is a measurement which requires considerable care and experience For wind speed the cups or propeller must be removed to avoid wind influencing the measurement. The torque watch adapter is attached to the shaft and the torque watch is inserted into the adapter and rotated until the shaft begins to turn The maximum torque from repeated tests is the starting torque. If manufacturers do not have a torque specification for their sensor, they should be asked to provide one

Orientation
by
Local Apparent Noon

Date of Observation ______________________________

Observer(s) ______________________ ______________________

Day/Time of WWV Synchronization ______________________________

Station Name ______________________________

____

Station Longitude	________ °	________ '	________ "
Ref ________			
Standard Meridian	________ °	________ '	________ "
Difference in degrees	________ °	________ '	________ "
Difference in time (x4)		________ *min*	________ *sec.*
Mean Time at Local Apparent Noon	________ *hr*	________ *min.*	________ *sec.*
Ref. ________			
True Noon Time ________ *date*	________ *hr.*	________ *min.*	________ *sec.*

Sitings	*True Heading*	*Target*

Figure 2.3.4. *Example of solar noon orientation form and tables.*

Table 169.

Ephemeris of the Sun[1]

All data are for 0ʰ Greenwich Civil Time in the year 1950. Variations of these data from year to year are negligible for most meteorological purposes, the largest variation occurs through the 4-year leap-year cycle. The year 1950 was selected to represent a mean condition in this cycle.

The ***declination*** of the sun is its angular distance north (+) or south (−) of the celestial equator.

The ***longitude*** of the sun is the angular distance of the meridian of sun from the vernal equinox (mean equinox of 1950.0) measured eastward along the ecliptic.

The ***equation of time*** (apparent − mean) is the correction to be applied to mean solar time in order to obtain apparent (true) solar time.

The ***radius vector*** of the earth is the distance from the center of the earth to the center of the sun expressed in terms of the length of the semimajor axis of the earth's orbit

[1] U. S. Naval Observatory, The American ephemeris and nautical almanac for the year 1950, Washington, 1948.

EPHEMERIS OF THE SUN

Date	Declination °	′	Longitude °	′	Equation of time m.	s.	Radius vector	Date	Declination °	′	Longitude °	′	Equation of time m.	s.	Radius vector
Jan. 1	−23	4	280	1	− 3	14	0.98324	Feb. 1	−17	19	311	34	−13	34	0.98533
5	22	42	284	5	5	6	.98324	5	16	10	315	37	14	2	.98593
9	22	13	288	10	6	50	.98333	9	14	55	319	40	14	17	.98662
13	21	37	292	14	8	27	.98352	13	13	37	323	43	14	20	.98738
17	20	54	296	19	9	54	.98378	17	12	15	327	46	14	10	.98819
21	20	5	300	23	11	10	.98410	21	10	50	331	48	13	50	.98903
25	19	9	304	27	12	14	.98448	25	9	23	335	49	13	19	.98991
29	18	8	308	31	13	5	.98493								
Mar. 1	− 7	53	339	51	−12	38	0.99084	Apr. 1	+ 4	14	10	42	− 4	12	0.99928
5	6	21	343	51	11	48	.99182	5	5	46	14	39	3	1	1.00043
9	4	48	347	51	10	51	.99287	9	7	17	18	35	1	52	1.00160
13	3	14	351	51	9	49	.99396	13	8	46	22	30	− 0	47	1.00276
17	1	39	355	50	8	42	.99508	17	10	12	26	25	+ 0	13	1.00390
21	− 0	5	359	49	7	32	.99619	21	11	35	30	20	1	6	1.00500
25	+ 1	30	3	47	6	20	.99731	25	12	56	34	14	1	53	1.00606
29	3	4	7	44	5	7	.99843	29	14	13	38	7	2	33	1.00708
May 1	+14	50	40	4	+ 2	50	1.00759	June 1	+21	57	69	56	+ 2	27	1.01405
5	16	2	43	56	3	17	1.00859	5	22	28	73	46	1	49	1.01465
9	17	9	47	48	3	35	1.00957	9	22	52	77	36	1	6	1.01518
13	18	11	51	40	3	44	1.01051	13	23	10	81	25	+ 0	18	1.01564
17	19	9	55	32	3	44	1.01138	17	23	22	85	15	− 0	33	1.01602
21	20	2	59	23	3	34	1.01218	21	23	27	89	4	1	25	1.01630
25	20	49	63	14	3	16	1.01291	25	23	25	92	53	2	17	1.01649
29	21	30	67	4	2	51	1.01358	29	23	17	96	41	3	7	1.01662
July 1	+23	10	98	36	− 3	31	1.01667	Aug. 1	+18	14	128	11	− 6	17	1.01494
5	22	52	102	24	4	16	1.01671	5	17	12	132	0	5	59	1.01442
9	22	28	106	13	4	56	1.01669	9	16	6	135	50	5	33	1.01384
13	21	57	110	2	5	30	1.01659	13	14	55	139	41	4	57	1.01318
17	21	21	113	51	5	57	1.01639	17	13	41	143	31	4	12	1.01244
21	20	38	117	40	6	15	1.01610	21	12	23	147	22	3	19	1.01163
25	19	50	121	29	6	24	1.01573	25	11	2	151	14	2	18	1.01076
29	18	57	125	19	6	23	1.01530	29	9	39	155	5	1	10	1.00986
Sept. 1	+ 8	35	157	59	− 0	15	1.00917	Oct. 1	− 2	53	187	14	+10	1	1.00114
5	7	7	161	52	+ 1	2	1.00822	5	4	26	191	11	11	17	1.00001
9	5	37	165	45	2	22	1.00723	9	5	58	195	7	12	27	0 99888
13	4	6	169	38	3	45	1.00619	13	7	29	199	5	13	30	.99774
17	2	34	173	32	5	10	1 00510	17	8	58	203	3	14	25	.99659
21	+ 1	1	177	26	6	35	1.00397	21	10	25	207	1	15	10	.99544
25	− 0	32	181	21	8	0	1.00283	25	11	50	211	0	15	46	.99433
29	2	6	185	16	9	22	1.00170	29	13	12	214	59	16	10	.99326
Nov. 1	−14	11	217	59	+16	21	0.99249	Dec. 1	−21	41	248	13	+11	16	0.98604
5	15	27	222	0	16	23	.99150	5	22	16	252	16	9	43	.98546
9	16	38	226	1	16	12	.99054	9	22	45	256	20	8	1	.98494
13	17	45	230	2	15	47	.98960	13	23	6	260	24	6	12	.98446
17	18	48	234	4	15	10	.98869	17	23	20	264	28	4	17	.98405
21	19	45	238	6	14	18	.98784	21	23	26	268	32	2	19	.98372
25	20	36	242	8	13	15	.98706	25	23	25	272	37	+,0	20	.98348
29	21	21	246	11	11	59	.98636	29	23	17	276	41	− 1	39	.98334

***Figure 2.3.4** (continued) (Reproduced with permission)*

For wind direction the procedure is the same but because the sensor usually has a potentiometer attached to the shaft, the range of the torque required to turn both the shaft and the potentiometer is higher than for wind speed This usually requires a second torque watch with a higher operating range For sensors where the vane cannot be easily or completely removed, the test must be done in a still room or enclosure with the sensor shaft vertical or perfectly balanced

It should be noted that an experienced instrument technician can detect the condition of a bearing assembly by "feel" with perhaps as much sensitivity as the torque watch. This talent should be used as a routine method for checking bearing condition for those programs which do not require documentation of data quality and do not have the torque watch capability Others should develop the capability

In general field calibrations should be as much like the bench calibrations as the field conditions and available equipment will allow. In addition, however, the field calibration must include those additional tests which relate to the system being installed Two examples of the additional tests are the orientation of the direction vane or fixed propeller assembly with respect to TRUE NORTH and the alignment of the sensors in the vertical operating position Field calibrations should be done at least every six months

2.3.5 *Installation*

Follow the general guidelines set forth in Section 2 2 6, "Preparation for Field Installation," and in Section 3, "Methods for Judging Suitability of Sensor Siting "

Wind vanes require orientation to true north Some manufacturers electrically orient the transducer in the housing and identify the northfacing side of the housing with an engraved mark, or they provide a flat surface for sighting toward north Other manufacturers supply, as an option, a mounting jig for keeping the vane in proper alignment for orientation

The most accepted procedure for determining true north involves shooting the North Star with a first-order theodolite Any textbook or handbook on land surveying will describe the technique and will contain all the necessary tables Best results may come from hiring a registered land surveyor to establish true north

Another acceptable method of establishing true north is by the location of the sun at true solar noon (see Figure 2.3 4)

T_{tsn} = (12:00:00) + [B(Long-15n) -A]

where T_{tsn} = local standard time of true solar noon
A = "Equation of Time" from "Ephemeris of Sun" tables (List, 1971)
B = 4 minutes per degree of longitude
Long = local longitude
n = number of time zones from Greenwich
n = 5 Eastern
n = 6 Central
n = 7 Mountain
n = 8 Pacific
n = 9 Yukon
n = 10 Alaska/Hawaii
n = 11 Bering

Alignment in the vertical is equally important. Studies have indicated that vertical misalignment of 1 degree may yield data errors of 10 percent or greater in measurement of turbulent parameters (Pond, 1968; Deacon, 1968; and Kraus, 1968) Vertical alignment should be established with a good carpenter's level or torpedo level at two points 90° apart in the horizontal

2.3.6 *Operation of a Wind Measuring System*

An operational check and calibration of the wind system is recommended after the installation has been completed and at intervals of at least every six months after operations begin

The use of tic-marks on chart rolls is very effective to indicate time of visit or some operation These are often made with event pens purchased with the recorders Whether manually or automatically actuated, the event pens can be energized to produce distinguishing marks corresponding to different times If the sensor is readily accessible, another simple means of establishing a tic-mark is to rotate the vane 360 degrees and note the time on the strip chart. Where strip chart recorders are used, time checks every 24 hours are desirable

Of course, documentation relating to date, time, etc , should be entered on each strip chart when it is installed and removed. The amount of data to be reduced or retrieved from properly annotated and logged strip charts will depend on program objectives in conjunction with the amount of the strip chart data needed All operational activities should be logged including those written on strip charts It is not possible to log too much information as long as it is consistent The problem is always with too little information, particularly time and date

2.3.7 *Preventive Maintenance (PM)*

Follow the general guidelines in Section 2.2.5, "Operational Checks and Preventive Maintenance." Physical checks of the equipment should be made as often as possible, and at least monthly These checks include an examination of the sensors and the readout equipment. At locations where pollution is heavy, it may be necessary to routinely change the bearings in both the anemometer and vane housing Oilless bearings should never be oiled. Bearings can be checked with a torque watch (see Section 2 3.4).

Recording equipment with pens and ink should be cleaned on a regular monthly schedule If the recorder is equipped with disposable felt tip pens, careful monitoring is recommended The fluctuations of the wind, as recorded by the pen, result in an average pen life of 2 or 3 days, so there may be a loss of data

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

2.3.8 *Audit Procedures*

Refer to Section 2.2 4, "Audits," for general guidelines A complete systems audit is necessary near the beginning of any wind measuring program Particular attention should be paid to sensor siting

Performance audits may include but should not be limited to repeating the field calibration on the sensors and associated cabling while they are still in place (see Section 2.3.4) The wind speed calibration procedure may involve rotation of the anemometer with a constant speed motor. When a synchronous motor is used for an audit there needs to be a method for measuring the rate of rotation and there needs to be AC power, usually 60 Hertz It may not be possible to get the power at the sensor location or even the site location It also may be troublesome to measure the rate of rotation if the transducer is a generator since generators often have electrical noise and the averaging of voltage samples is less accurate than counting revolutions in an accurately known time gate.

An alternative method is to challenge the anemometer shaft with at least two known *average* rates of rotation The rates should represent common low wind speeds; somewhere in the ranges 1-2 m/s and 5-7 m/s for example One should audit the low end of the speed range because that is where the data are most important for air quality applications and where error estimates are most valuable. It is also easy to know the accurate average rate of rotation by counting revolutions (by switch or manually) over a period of time significant to the data period (2 to 15 minutes typically) where the number of rotations is large enough that the uncertainty over the time period is less than one percent. The elapsed time measurement will always be accurate enough so that the average rate of rotation will be within one percent of the reading Since an average is used, the motor driving the shaft does not need to be synchronous and a DC motor driven by a battery will give freedom from the commercial power requirement It is important to have nearly or exactly the same time interval used by both the motor drive and the output reading The only part of the system challenged by this method is the measurement and recording of the rate of rotation expressed as wind speed. There is no test of the rate of rotation of the sensor as a function of wind speed, that relationship is either given by the manufacturer as a nominal value or was determined by a wind tunnel test. If a wind tunnel test was made initially and the sensor is identified by serial number and shows no sign of deformation in shape, it is reasonable to assume the sensor rate of *rotation vs. wind speed relationship* has not changed It is not necessary to wind tunnel test every six months or year If, on the other hand, a wind tunnel test has not been done and the program requires documentation of accuracy, a wind tunnel test should be done or an audit with a collocated transfer standard (CTS) The CTS has the advantage of challenging the entire system in naturally turbulent flow The CTS must be well sited to measure representative flow without mutual interference A period of at least 12 hours (half of a diurnal cycle) should be used to obtain as much range comparison as is practical

The wind direction audit procedure should concentrate on output when the vane is aimed at known sites The direction to and from a distant landmark should be determined by independent methods Map location is best if a good map is used (USGS, airways or equivalent) and the site can be accurately located. Another method is to use a north finding technique such as described in Section 2.3.5 and to measure the angle between north and the landmark with a theodolite or a sextant. The direction vane should be taped or clamped in the direction desired so a steady reading can be accurately made. If a sigma theta measurement is included in the system, this would be a good time to verify zero.

If a CTS is used, the comparison of averages will be subject to orientation differences (bias) and perhaps others caused by different dynamic performance characteristics and different averaging methods. When properly exposed, the CTS gives the best estimate of accuracy when operating in a naturally turbulent flow. Collocated sensors are within 10 m of each other in the horizontal and one meter in the vertical according to Hoehne (1971). Data taken while the wind is within ±30° of the line between the sensor being audited and the CTS should not be used.

2.4 Temperature Measurements

2.4.1 *Introduction*

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

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

Resistance Temperature Detectors (RTD) - The RTD operates on the principle that the electrical resistance of a pure metal increases with temperature. Although RTD sensors are made using silver, copper, and nickel wire, platinum wire is the best material because of its superior linearity and stability characteristics, high sensitivity, and resistance to corrosion. The RTD probe is encased in a protective stainless steel housing composed of an insulating core wrapped with platinum wire. The resistance of the wire is measured by a bridge circuit in a signal conditioner. The RTD operates at a much lower resistance to temperature ratio than the linear thermistor. RTD's used most often in meteorological work have a coefficient of resistance change on the order of 0.4 ohms per degree Celsius, and are more sensitive to lead resistance errors than are thermistors. "Three wire" and "four wire" systems are configurations that automatically compensate for lead resistance.

Liquid-In-Glass-Thermometers - Most of these thermometers are 10-1/2-inch glass tubes with a uniform capillary bore and a liquid reservoir or bulb at the bottom. Thermometers are usually mounted on a stainless steel back with the bulb protruding to allow free air circulation. Volumetric expansion and contraction of the operating liquid provides the measure of temperature. The liquid is usually mercury but may be a mixture of ethyl alcohol and red dye. Thermometers filled with alcohol are called spirit thermometers. Though inherently less accurate than a mercury thermometer, the spirit thermometer must be used where extremely cold temperatures are anticipated because mercury will freeze at -38°C.

Thermocouples - Because of its complex circuitry and somewhat limited accuracy, the thermocouple is not a popular operational meteorological sensor, although its vast capabilities make its use in other temperature measurement applications quite common. The thermocouple operates on the principle that when two different metals are joined, a small voltage with a temperature-dependent magnitude is generated. By comparing this voltage to the voltage generated by the same two metals joined at a temperature-controlled reference junction (ice point), the ambient temperature can be determined.

Deformation-Type Thermometers - This category of thermometer depends upon the thermal expansion and contraction of metals or liquids. The response to temperature changes is actual physical movement of the sensor mechanism, which is mechanically transmitted through a system of levers to a thermograph, where a continuous temperature trace is produced. The most common deformation-type thermometers are the bimetallic thermometer, where vastly different thermal expansion properties of two mated metal strips produce deformation; the Bourdon tube thermometer, where a coiled, hollow, spirit-filled, flexible metal tube changes shape with the thermal expansion and contraction of the internal fluid; and the mercury-in-steel thermometer, where the pressure produced by thermal expansion of the mercury is transmitted to a Bourdon tube. With the coming of age of the quick-response electronic recording sensor system, slow-reacting thermographs with their requirement of manual data reduction are slipping in popularity.

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

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

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

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

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

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

2.4.1.2 Solar Radiation Shields-The most serious problem encountered in environmental thermometry is radiation error, which can amount to several degrees Celsius at midday. Early attempts to combat radiation error took the form of instrument shelters, such as the all-wood, louvered, double-roofed cotton-region type. Much better results in reducing radiation error have been achieved with aspirated radiation shields (Figure 2.4.1)

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

Mechanically Aspirated Radiation Shields - This type of radiation shield is used where power is readily available to

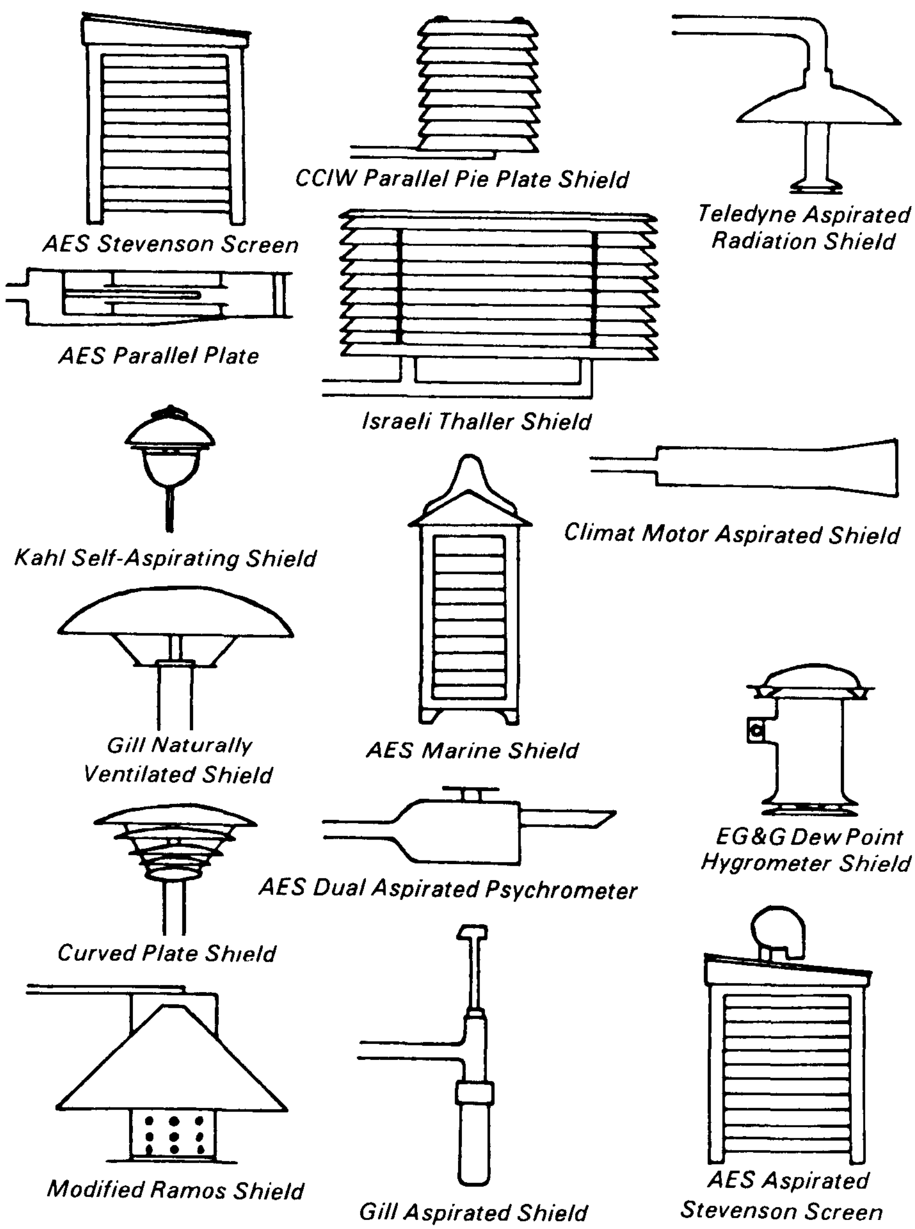

Figure 2.4.1. *Examples of various radiation shields (McTaggart-Cowan and McKay, 1976).*

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

2.4.1.3 Temperature Data Requirements-In general, measuring temperature with an accuracy greater than 0 5°C may not be necessary. Extreme daytime horizontal temperature gradients are well documented (Hoffmann, 1965, and Department of the Army, 1975) However, certain circumstances require more accuracy or relative accuracy for differential temperature measurements For example, a temperature gradient measurement requires a relative accuracy of temperature or an absolute accuracy of temperature difference of 0.1°C. This is true for the low level local surface gradient measurement between 2 m and 10 m above the ground or for the more conventional measurement between 10 m and 60 m Also, if humidity is measured by the wet-bulb and dry-bulb difference, sensors should be matched so that small differences are meaningful.

The very fact that the atmosphere is a turbulent, differentially heated fluid should remind any investigator that a temperature recorded to the nearest tenth of a degree is representative of only a very small volume of air for a very short period of time. All routine monitoring applications of temperature data, be they air temperature or temperature gradient, will be expressed as a longer term average.

2.4.2 *Procurement*

In purchasing a suitable temperature sensor system, follow the general guidelines advanced in Section 2 2 1, "Instrument Procurement " Pay particular attention to data requirements, including management and reduction. Evaluate the measurement site or sites, giving consideration to power requirements, cable lengths, possible signal interference, sensor mounting and exposure, and housing requirements for ancillary equipment

2.4.3 *Acceptance Testing*

Follow the general guidelines set forth in Section 2.2.2, "Acceptance Testing " The general response of the sensor can be checked by placing it alternately in warm and cold water and observing the output. This unnatural exposure may damage some types of sensors It is prudent to keep the sensor assemblies dry by covering them with a thin plastic bag. This prevents any "wicking" of water into electronic assemblies.

If the time constant is to be tested (important primarily for research applications), it should be done in the aspirator at the normal operating flow rate. The aspirator should provide a flow by the sensor of about 5 m/s The flow can be checked with a pitot tube or hot wire anemometer. If the flow seems weak, check the motor output, the fan mechanisms for binding or damage, and the air passages for obstructions

2.4.4 *Calibration*

Refer to the general notes in Section 2.2 3, "Calibrations "

Bench Calibration - In bench calibrating a temperature sensor, one may use material changes of state to obtain an absolute reference temperature For meteorological purposes, the triple point of water is one such absolute reference that falls within the normal range of ambient boundary layer temperatures It requires special equipment to produce this temperature In calibrating a remote electronic sensor, all ancillary equipment, including cables, signal conditioners, and recorders, should be hooked up as close to field configuration as is possible to achieve in the laboratory Deformation-type instruments are usually returned to the manufacturer for calibration A minimum of two reference points is required All calibrations should be performed in stable thermal masses in insulated containers, such as Dewar flasks or Thermos® bottles (Figure 2 4 2) A precision mercury-in-glass thermometer or other calibrated thermometer is required. This instrument should be certified as having been calibrated according to National Bureau of Standards (NBS) procedures (Lockhart and Gannon, 1978). A bath must be continuously agitated either by hand or with a mechanical stirrer that is thermally insulated so as not to act as a heat sink or source A solid mass in near thermal equilibrium may also be used The sensor must be completely submerged, held with an insulated clamp, and not allowed to contact either the stirrer, the reference thermometer, or the sides of the flask. If an ice bath is used, it should contain distilled water and ice slurry made from distilled water (Wang, 1975) For the second reference, best results will be obtained by using water at near-ambient temperature to reduce heat exchange problems. When temperatures have stabilized, record the readings of both the sensor and the reference thermometer

If the calculated error at each calibration point falls within the accepted bounds for the particular sensor, the calibration can be certified If adjustments are required, the calibration checks must be repeated

The bench calibration of a differential temperature system (often called delta T) requires both sensors to be at exactly the same temperature For this, thermal stability is much more important than accurate knowledge of the temperature. If the zero difference is verified at two temperatures (such as near 0°C and 40°C), then it is also verified that each sensor is reacting with the same output vs temperature transfer function When two are alike it is reasonable to expect they are following the manufacturer's nominal transfer function. The differencing circuit can be calibrated by using substitute sensors

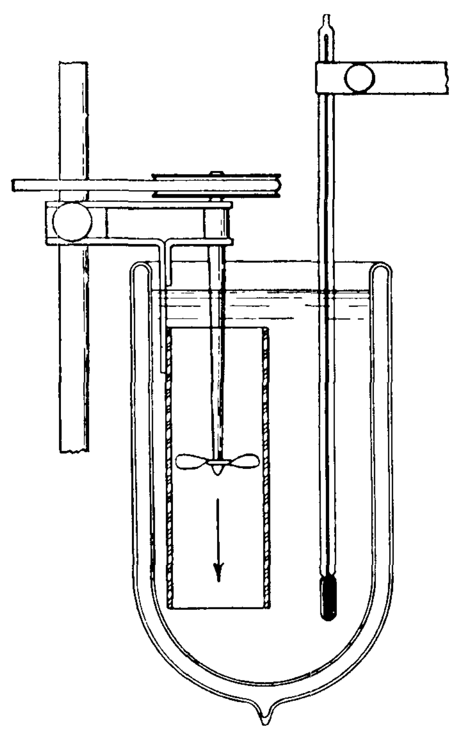

Figure 2.4.2 *A simple bath for calibrating thermometers (Middleton and Spilhaus, 1953).*

(resistance boxes, etc.) with an accuracy consistent with the 0 1°C goal It is difficult to maintain differential thermal masses of known temperature to achieve this calibration

Field Calibration - If at all possible, the bench calibration procedures should be duplicated in the field Obviously, for this to be possible, the user must have a mobile laboratory or on-site access to a sheltered work area To perform a proper calibration, the sensor must be removed from its housing For electronic sensors, all cables must remain attached If no shelter is available, calibration must be done during a period of calm winds under either cloudy skies or at night under inversion conditions If these minimum conditions cannot be achieved, then field calibration is not possible and a calibration check will be performed instead If the check indicates that the calibration is off, then the instrument must be brought in for a bench calibration

In addition to the sensor checks outlined above, circuitry checks of remote sensing systems are often made by replacing the electronic sensor with resistors of known value Some systems include built-in reference resistors allowing easy "internal" calibration checks

Both the bench and field calibration methods described above deal with the transducer and measurement system but ignore the coupling by the radiation shield A collocated transfer standard (CTS) of known accuracy may be used in an operational way for a period of time at least one half a diurnal cycle to maximize the range being tested With hourly (or shorter) averages taken over exactly the same periods of time as the monitoring system and with assurance of noninterference with the air which reaches each sensor, an estimate of accuracy for the *complete* measurement system can be made Errors in coupling from solar or terrestrial radiation cannot be adjusted for The solution for this problem will usually require a better radiation shield

2.4.5 *Installation*

Follow the general guidelines set forth in Section 2 2 6, "Preparation for Field Installation " The shakedown period for a temperature sensor need only last long enough for the diurnal temperature cycle to be defined and a number of comparisons against an NBS-certified thermometer to be made, usually a few days Following bench calibration and shakedown, the sensor is shipped to the field Proper siting of temperature sensors is described in Section 3, "Methods for Judging Suitability of Sensor Siting." Louvered shelter doors and mechanical aspirator openings should be oriented north in the northern hemisphere Tower-mounted sensors should have downward facing aspirated shields cantilevered on a boom not less than one tower diameter in length to minimize the effects of sensible heat from the tower structure Installations on the sides of buildings or through windows of buildings cannot be expected to provide unbiased data All wire connections should be made as soldered joints, without acid-type fluxes, using approved soldering techniques; "cold joints" are one of the greatest sources of difficulty in resistance thermometry Proper grounding procedures will minimize problems associated with potential gradients and thunderstorm activity

Once installed, a calibration check should be made At least one further cursory operational check should be made 24 hours after the instrument has been placed on line

2.4.6 *Field Operation of a Thermometry System*

As part of the quality assurance program, a field calibration should be performed a minimum of once every 6 months Calibration checks should be made monthly A technician should visit the site as often as possible, even daily No site should go unattended for longer than a month Each time the site is visited, a comparison should be made against a reference thermometer A side-by-side comparison is desirable although this may not be practical with certain tower installations The data should be inspected for a reasonable diurnal temperature pattern Where strip chart recorders are used, time checks every 24 hours are desirable Data retrieval will depend upon program objectives, but even for climatological programs, data should be retrieved monthly All operational activities during a site visit should be logged

2.4.7 *Preventive Maintenance*

Temperature sensors are basically maintenance free Most PM on thermometry systems is concerned with housings Instrument shelters must be cleaned as often as local weathering conditions require The air passageways and screens in radiation shields, both aspirated and naturally ventilated, should be cleaned out at least once every month The aspirator motor should be checked during each visit. For remote sites or where data collection is critical, the aspirator motor should be changed periodically as recommended by the manufacturer. Lubricate the aspirator system as required, but not oilless bearings. The spare parts inventory should include a sensor and aspirator motor The most common cause of component failure is lightning. Obviously a system damaged by lightning will require recalibration after repairs are made All PM activities should be logged

2.4.8 *Audit Procedures*

Refer to Section 2 2.4, "Audits," for general guidelines.

A performance audit on a thermometry system is simply a calibration check following the procedures previously outlined in Section 2.4.4. If a field calibration check is not physically possible or practical, then the audit may consist of running a side-by-side comparison using a second complete sensor system with known accuracy and response characteristics Inserting a calibrated audit sensor into the same housing with the sensor being audited may be a poor procedure, as the second sensor may alter the flow characteristics and sensible heat regime within the housing. There is no requirement dictated by temperature sensor characteristics for a regular schedule of temperature instrument audits Of course, a system audit should be performed near the beginning of a measurement program. Other audits should be geared to program goals and may be random events.

2.5 Humidity/Dew Point Measurements

2.5.1 *Introduction*

Humidity is a general term for the water-vapor content of air. Other, more specific, terms for humidity include absolute humidity, relative humidity, specific humidity, mixing ratio, and dew point (Huschke, 1959). This section discusses the measurement of relative humidity and dew point

Relative humidity (RH) is a dimensionless ratio of the actual vapor pressure of air to the saturation vapor pressure at a given dry bulb temperature Dew point is the temperature to which air must be cooled, at constant pressure and constant water vapor content, to be saturated with respect to liquid water. Frost point is the temperature below 0°C at which air is saturated with respect to ice

There are many ways to measure the water vapor content of the atmosphere. These can be classified in terms of the six physical principles (Middleton and Spilhaus, 1953) listed in Table 2 5 1 Examples of instruments for each technique are provided.

Table 2.5.1. Principles of Humidity Measurement

● *Reduction of temperature by evaporation*	*- psychrometer*
● *Dimensional changes due to absorption of moisture, based on hygroscopic properties of materials*	*- hygrometers with sensors of hair, wood, natural and synthetic fibers*
● *Chemical or electrical changes due to absorption or adsorption*	*- electric hygrometers such as Dunmore Cell; lithium, carbon, and aluminum oxide strips; capacitance film*
● *Formation of dew or frost by artificial cooling*	*- cooled mirror surfaces*
● *Diffusion of moisture through porous membranes*	*- diffusion hygrometers*
● *Absorption spectra of water vapor*	*- infrared and UV absorption; Lyman-alpha radiation hygrometers*

Instruments such as diffusion hygrometers that involve the diffusion of moisture through porous membranes are used primarily in research programs. The same is true of instruments that utilize the absorption spectra of water vapor, such as infrared and ultraviolet hygrometers, and Lyman-alpha radiation hygrometers This class of instrument requires frequent attention and represents a major investment in procurement and maintenance costs.

Psychrometry identifies a basic technique for deriving both relative humidity and dew point temperature from a pair of thermometers—a dry *bulb* thermometer that measures the ambient temperature, and a wet *bulb* thermometer. The reservoir of the wet bulb thermometer is covered with a muslin wick When the wick is moistened and the thermometer ventilated, the indicated temperature is related to the amount of evaporative cooling that can take place at the existing ambient temperature, water vapor partial pressure, and the atmospheric pressure (Figure 2 5 1).

The temperature sensors in a *sling psychrometer* are usually mercury- or alcohol-filled thermometers The same is true of portable motor-operated psychrometers, but the psychrometric principle has been used with sensors made of thermocouples, wire-wound resistance thermometers, thermistors, and bimetal thermometers Relative humidity and dew point are easily determined by observing the difference between the dry bulb and the wet bulb—the wet bulb depression—and then referring to psychrometric tables, charts, or calculators One must be certain to use computed values for the atmospheric pressure range of the location where the observation is taken

More measurements of atmospheric water vapor have probably been made with the sling psychrometer than by any other manual method When properly used and read, the technique can be reasonably accurate, but it is easily misused. The most important errors are from radiation, changes during reading, and parallax The Assmann psychrometer continuously aspirates the thermometers and protects them from radiation which allows time and accessibility for a careful reading to avoid parallax (a parallax avoiding guide to keep the eye perpendicular to the meniscus is best). For good accuracy, particularly where a variety of observers are taking measurements, an Assmann or equivalent type psychrometer is recommended. One should use the psychrometric tables with dew point values for the altitude (pressure) where measurements are being made.

Hygrographs, which record relative humidity, or *hygrothermographs,* which record both relative humidity and temperature, usually incorporate human hair as the moisture-absorbing sensor. Other instruments with sensors that respond to water vapor by exhibiting dimensional changes are available They are made with elements such as wood, goldbeater's skin (an animal membrane), and synthetic materials, especially nylon.

Instruments that utilize the hygroscopic characteristics of human hair are used most frequently, primarily because of availability The hygrograph provides a direct measure of relative humidity in a portable instrument that is uncomplicated and is relatively inexpensive There are limitations in accuracy below 20 percent relative humidity and above 80 percent that may be unacceptable, as

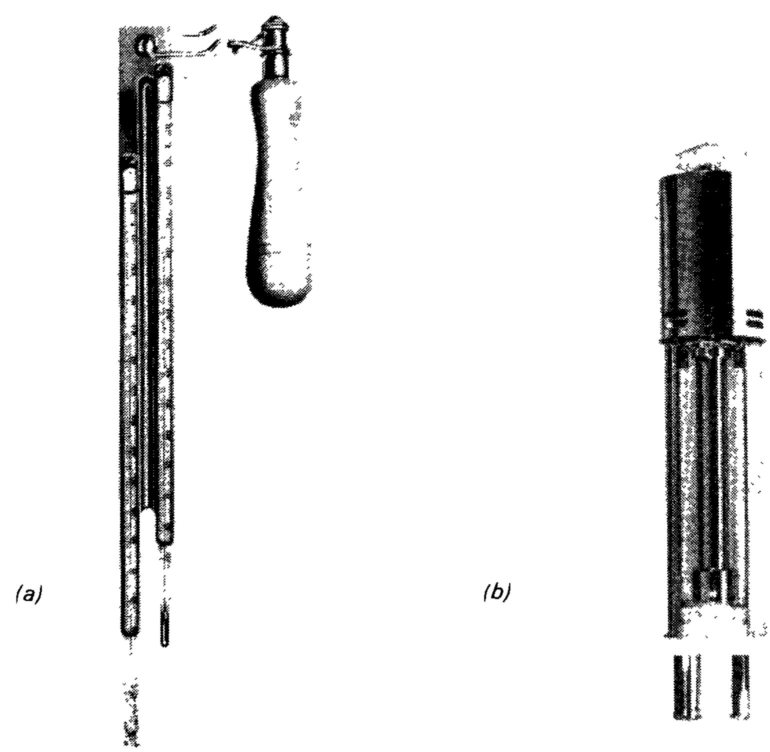

Figure 2.5.1 *An official National Weather Service sling psychrometer (a) and an Assmann psychrometer (b).*

well as limitations for applications at low temperatures. Atmospheric Environment Services of Canada has found that Pernix, a specially treated and flattened hair element, can be used at temperatures below freezing without serious errors. The hygrothermograph made to an NWS specification incorporates human hair as the humidity sensor and bourdon tube (a curved capsule filled with alcohol) as the temperature sensor

Dew point hygrometers with continuous electrical outputs are in common use for monitoring One dew point hygrometer was originally developed for air conditioning control applications under the trade name *Dewcel* (Hickes, 1947) and was adopted to meteorological use (Conover, 1950) From the trade name, the generic term *dew cell* has evolved that now identifies an instrument made by several manufacturers This device determines moisture based on the principle that for every water vapor pressure in contact with a saturated salt solution, there is an equilibrium temperature at which this solution neither absorbs nor gives up moisture to the surrounding atmosphere.

The dew cell, also known by the trade name *Dew Probe*, consists of bifilar wire electrodes wrapped around a woven glass cloth sleeve that covers a hollow tube or bobbin. The sleeve is impregnated with a lithium chloride solution (Figure 2 5 2) Low-voltage a.c is supplied to the electrodes, which are not interconnected but depend on the conductivity of the atmospherically moistened lithium chloride for current flow The temperature sensor in the tube is usually a resistance thermometer, but can be a thermistor, thermocouple, bimetal thermometer, capillary system, or any sensor calibrated for the proper temperature-to-dew-point relationship

In the early 1960's, the technique of detecting the dew point on a *cooled mirror surface* evolved into a production-type unit This unit was automatically operated and had an optical dew-sensing system that incorporated thermoelectric cooling (Francisco and Beaubien, 1963) Four manufacturers now produce a meteorological type, thermoelectric, cooled-mirror dew point instrument (Mazzarella, 1977) Three of these instruments cover the range of -50° to +50°C Linear thermistors are used to measure the mirror temperature in three of the units, a platinum wire sensor is used in the other All are designed with simultaneous linear output signals for T_{dp} (dew point temperature) and T (ambient temperature) Two of the manufacturers make claims to NBS-traceability with stated dew point accuracies ranging from ±0.2° to ±0.4°C and ambient temperature accuracies ranging from ±0 1° to ±0.5°C All incorporate some form of standardization that involves clearing the mirror by heating, either automatically or manually. Although complex in design and operation, this type of cooled-mirror hygrometer is considered to be a functional standard

In recent years, two other sensors for humidity have been used on tower installations for atmospheric pollution studies. One involves the use of an organic seed, cut and coupled to a strain gage. In principle, absorption of moisture in the seed results in distortion, which is converted to an electrical signal by the strain gage assembly. Reports on performance are mixed. Certainly the applications are limited, and the approach does not represent a technological advance By contrast, the *thin film capacitor*, designed primarily for radiosonde applications, incorporates advanced technology (Suntola and Antson, 1973) Reports of users have been mixed, with a common complaint of poor performance in polluted atmospheres. The capacitor may still be considered a sensor for some research applications on towers

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

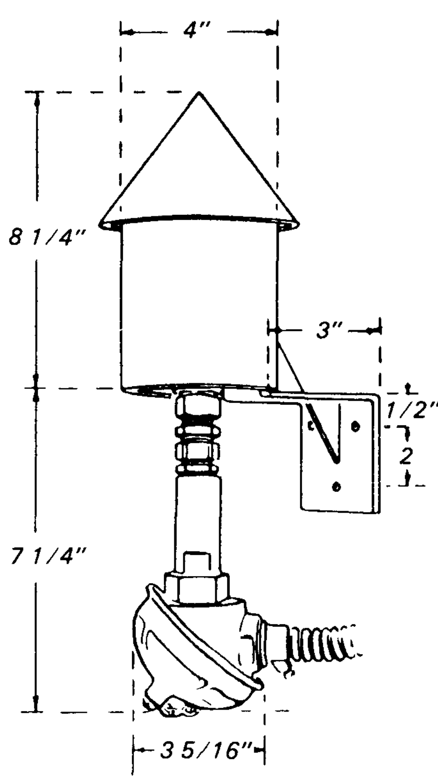

Figure 2.5.2. *A typical Dewcel sensor housing and transmitter.*

It has long been recognized that there are some limitations in using the dew cell instrument (Acheson, 1962) The lowest relative humidity it can measure at a given temperature is the ratio of the vapor pressure of a saturated solution of LiCl to that of pure water. This is calculated to be 11 8 percent RH. A second limitation is that at -65.6°, -20.5°, +19.0°, and +94.0°C, LiCl in equilibrium with its saturated solution undergoes a phase change Errors in dew point measurements occur at -69°, -39°, -12°, and +40°C. This problem is inherent in the use of LiCl and cannot be eliminated. It is estimated that the accuracy of the LiCl saturated salt technique is 1.5°C over the range of -30° to 30°C.

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

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

For meteorological applications, the dew cell element should be enclosed in a *weatherhood* to protect it from precipitation, wind, and radiation effects. This type of element functions best in still air. Some *aspirated radiation shields* are designed, in keeping with these specifications, to house both a temperature sensor, which requires ventilation, and a dew cell, which requires only the smallest amount of air flow (Figure 2.5.3). The miniaturization of the dew cell has created some problems related to excessive air flow and solar radiation that remain only partially solved

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

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

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

Both the dew cell and the cooled-mirror type instruments have applications on 10-meter or taller tower installations for pollution studies, providing the sensors are housed in the recommended shields with little, if any, aspiration for the dew cell and the recommended rate of aspiration for the cooled-mirror design is selected

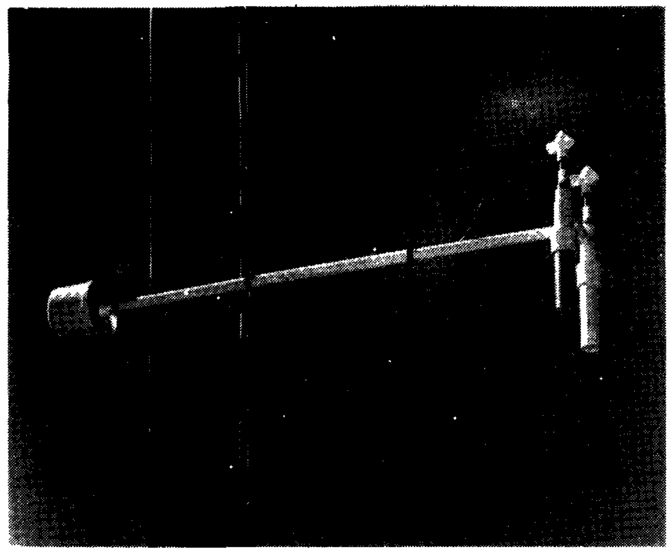

Figure 2.5.3. *A pair of tower-mounted Gill aspirated radiation shields for housing temperature and dew point sensors (R M Young Co.).*

2.5.2 *Procurement*

In purchasing a suitable humidity/dew point measuring system, follow the general guidelines advanced in Section 2 2 1, "Instrument Procurement "

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

When patents expired on the original Dewcel, a number of similar units appeared on the market In light of problems which have existed in the past, it is prudent to specify accuracy of the humidity system when it is operating as a system in the atmosphere Problems with ventilation rates will be quickly exposed by this requirement It is not recommended to purchase components to patch together in a system Corrosion in polluted atmospheres can be avoided by selecting optional 24-carat gold windings, provided cost is not prohibitive. If dew point alone is to be measured, the standard weatherhood is a proper choice If both temperature and dew point are to be measured, it may be advantageous to purchase a standard shield that provides a housing for the dew cell and a separate aspirated compartment for the temperature probe

Optical cooled-mirror dew point systems are now available commercially from four manufacturers, all of which incorporate either linear thermistors or platinum resistance temperature devices

2.5.3 *Acceptance Testing*

Follow the general guidelines set forth in Section 2.2.2, "Acceptance Testing " Test at least the ambient atmosphere at one point in normal wind and radiation

2.5.4 *Calibration*

Refer to the general notes in Section 2 2 3, "Calibrations " The procedure for calibrating the thermometers in a psychrometer is essentially the same as any thermometer calibration (see Section 2 4 4)

Both the dew cell and the cooled-mirror hygrometer can be checked for approximate calibration accuracy with a motor-operated psychrometer Their performance should be verified under stable conditions at night or under cloudy conditions during the day Several readings taken at the intake of the aspirator or shield are recommended Bench calibrations of these more sophisticated units must be made by the manufacturer The electronics portion of some instruments may be calibrated by substitution of known resistances in place of the temperature sensor This procedure, if appropriate, is described in the manufacturer's operating manual for the instrument

2.5.5 *Installation*

Follow the general guidelines set forth in Section 2.2.6, "Preparation for Field Installation" and in Section 3, "Methods for Judging Suitability of Sensor Siting"

Dew point measuring equipment on a tower should be installed with the same considerations given to temperature sensors. Reference has already been made to the weatherhood as a shield for the dew cell and to an aspirated shield for the cooled-mirror instrument. At some installations, success has been reported in mounting these housings so that they are close to the tower framework on the north-facing side. This minimizes the effects of direct solar radiation and provides a rigid support, especially for the cooled-mirror sensor, which requires a stable mounting surface Another consideration in mounting these devices inboard involves servicing Inboard mounting makes recharging the dew cell with lithium chloride and cleaning the reflective surface of the cooled-mirror hygrometer much easier

2.5.6 *Field Operation and Preventive Maintenance*

Note the guidelines in Section 2 2 5, "Operational Checks and Preventive Maintenance"

Field calibration checks should be made at least monthly on dew cell type units The use of gold wire windings around the LiCl cylinder minimizes corrosion problems in polluted atmospheres. Periodic removal and washing of old lithium chloride, followed by recharging with a fresh solution, improves data reliability

Once a mercury or alcohol liquid-in-glass thermometer is calibrated, there is no need for recalibration, unless it is to be used for reference or as a transfer standard Errors in wet bulb temperatures are most frequently the result of an improperly installed or dirty muslin wick, the repeated use of tap water instead of distilled water, or human error in reading Wicking material used on psychrometers must be washed to remove traces of sizing and fingerprints Once cleaned, the material is tied at the top of the thermometer bulb and a loop of thread placed around the bottom so the thermometer bulb is tightly covered To prevent solid materials from collecting on the cloth and preventing proper evaporation, the wick should be wet with distilled water Of course, slinging or motor aspiration should be done in the shade, away from reflected or scattered radiation, at a ventilation rate of about 3 to 5 m/s Many technique-related errors are minimized by using an Assmann-type, motor-operated psychrometer, providing the instrument is allowed to assume near ambient conditions prior to use.

The cooled-mirror instruments require *no calibration* except for the minor temperature sensor. Depending on environmental conditions, the mirror is easily cleaned with a Q-Tip® dipped in the recommended cleaning fluid, usually a liquid with an alcohol base. While the accuracy of a psychrometer is inferior to that of the optical chilled mirror system, an occasional check at the intake to the sensor shield is recommended under the provisions specified earlier

All operational and PM activities should be logged. Data retrieval will be dependent upon program objectives.

2.5.7 *Audit Procedures*

Refer to Section 2.2.4, "Audits," for general guidelines. Instrument audit procedures for hygrometry systems follow calibration procedures. A systems audit should be performed near the beginning of a field measurement program

The performance audit of a humidity measuring system should be based upon a comparison with a collocated transfer standard (CTS) Parts of the system can be tested by conventional electronic tests, but this avoids so much of the measurement process that it should only be used to augment the total system test The CTS may be any qualified instrument The most accurate type is the cooled-mirror dew point instrument. The Assmann-type psychrometer with calibrated thermometers traceable to NBS is acceptable for most data applications. It is also most convenient since it does not require commercial power and can be carried to elevated levels on a tower.

Given the qualifier that humidity is a very difficult measurement to make, a rule of thumb for judging the accuracy of a humidity monitoring system with an Assmann as the CTS is as follows: when the CTS and the challenged system agree in dew point temperature to within 1°C, the challenged system is assumed to be within 0 5°C of the true value This arbitrarily assigns an uncertainty in dew point temperature of ±0 5°C for the Assmann which is true for most of the range

2.6 Solar Radiation

2.6.1 *Introduction*

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

Quantitatively, solar radiation is described in units of energy flux, either W/m^2 or $cal/cm^2 \cdot min$. When measured in specific, narrow wavelength bands, solar radiation may be used to evaluate such air pollution indicators as turbidity, amount of precipitable water, and rates of photochemical reactions. However, this manual will cover only broadband measurements and sunshine.

The generic term, radiometer, refers to any instrument that measures radiation, regardless of wavelength. Shortwave radiation has wavelengths less than 4 micrometers (μm) and is subdivided as follows.

Ultraviolet (UV)	0.20 μm to 0.38 μm
Visible	0.38 μm to 0.75 μm
Near-infrared	0.75 μm to 4 00 μm

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

Pyranometers are instruments that measure the solar radiation received from the hemispherical part of the atmosphere it sees, including the total sun and sky shortwave radiation (Figure 2.6.1). Most pyranometers incorporate a thermopile as sensor Others that measure a narrower, shortwave bandwidth, use a silicon photovoltaic cell as a sensor The *spectral pyranometer* with two hemispherical domes is designed to measure sun and sky totally or in defined wavelengths. This is achieved by substituting one of several colored Schott glass filter domes for the clear glass outer dome

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

Net radiometers or *net pyrradiometers* are designed to measure the difference between downward and upward total radiation, including the total incoming shortwave and longwave radiation and the total outgoing shortwave and longwave radiation. There are two basic types of net radiometers The ventilated plate type, often referred to by the name

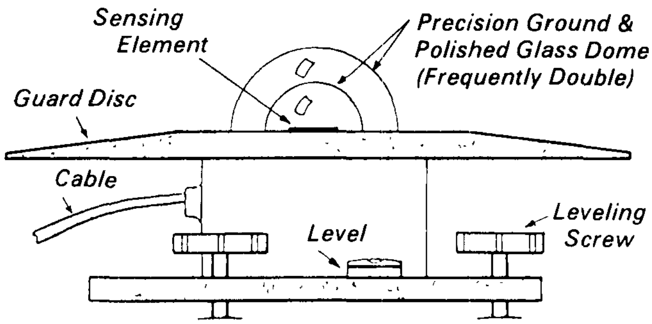

Figure 2.6.1. *The features of a typical pyranometer (Carter, et al., 1977)*

of the designers (Gier and Dunkle), is more popular in research applications than the type with hemispherical polyethylene domes originally designed by Funk. Both incorporate thermopiles with blackened surfaces. Because net radiometers produce a signal with a positive sign when the incoming radiation exceeds the outgoing, the recording equipment must be designed with an offset zero.

Sunshine recorders are designed to provide information on the hourly or daily duration of sunshine. Only one commercially available, off-the-shelf type of sunshine recorder is now available. This is the Campbell-Stokes design (Figure 2.6.2), designated as the interim reference sunshine recorder

Figure 2.6.2. *A Campbell-Stokes Sunshine recorder Department of the Army, 1975).*

"IRSR" by the World Meteorological Organization. The device consists of a glass sphere 10 cm in diameter mounted in a spherical bowl. The sun's rays are focused on a card that absorbs radiation and changes color in the presence of sunlight. The recorder is used infrequently in the United States but extensively abroad, primarily for the collection of climatological data. The National Weather Service routinely uses a Sunshine Switch, which incorporates one shaded photocell and one exposed photocell.

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

Pyranometer Characteristics - The pyranometer is not to be confused with the pyrheliometer, "an instrument for measuring the intensity of direct solar radiation at normal incidence" (WMO, 1971). The pyrheliometer is mounted in a solar tracker, or equatorial mount, automatically pointing to the sun as it traverses from east to west (Figure 2.6.3). By contrast, the pyranometer is mounted facing toward the zenith. Ideally, the response of the thermopile sensor in the pyranometer is proportional to the cosine of the angle of the solar beam and is constant at all azimuth angles. This characteristic is known as the Lambert Cosine Response, an important characteristic of pyranometers. For the majority of applications related to atmospheric pollution, Class 2 and Class 3 are satisfactory.

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

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

2.6.2 *Procurement*

In purchasing a solar radiation measurement system, follow the general guidelines advanced in Section 2.2.1, "Instrument Procurement." Many types of radiation instruments have been developed, especially in recent years, because of an increasing interest in environmental considerations (Gates, 1962), meteorological research (Monteith, 1972), and solar energy (Carter, et

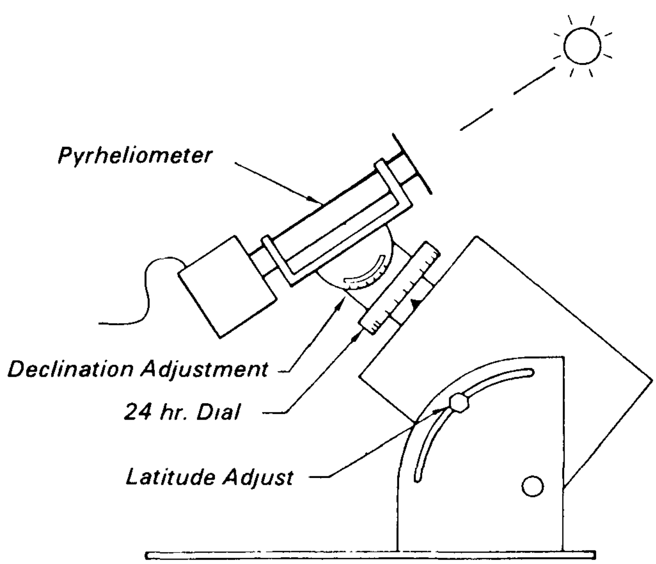

Figure 2.6.3. *Features of a typical pyrheliometer and tracking mount (Carter et al., 1977)*

al., 1977). Except for special studies, the requirements for relating radiation to stability can be satisfied by purchasing sensors of Class 2 or Class 3 as identified by the WMO Class 2 sensors offer the advantage of providing data comparable to that collected at National Weather Service stations and at key locations of DOE. The sensors to be specified should be commercially available, field proven by the manufacturer for several years, and have the technical requirements established by WMO standards An American Society for Testing and Materials (ASTM) standard is now under consideration When purchasing a recorder or integrator, one must match the calibration factor or sensitivity of the sensor to the readout equipment It must be recognized that the signals from net radiometers, in contrast to pyranometers, require zero-offset capability to accommodate both negative and positive voltage outputs

2.6.3 *Acceptance Testing*

Follow the general guidelines set forth in Section 2 2.2, "Acceptance Testing " Physical inspection of the relatively fragile pyranometers or net radiometers immediately after delivery of the instrument is important. One must be sure that the calibration data have been received and that the data correspond to the serial number of the instrument. Storage of this information will prove helpful when the time comes to have the calibration of the instrument checked, or to replace the sensor or readout device Few organizations are equipped or staffed to bench-test a radiometer to verify calibration, but a quick determination can be made indoors as to whether the sensor and recorder or integrator system is operating by exposing the sensor to the light of a tungsten lamp It may be necessary to place the instrument fairly close to the lamp Covering the sensor for several hours will ensure that the system is not "dark counting "

2.6.4 *Calibration*

Refer to the general notes in Section 2.2 3, "Calibrations " The user of a pyranometer or net radiometer is normally not equipped to calibrate the sensor The best the user can do is to perform field calibration checks on two clear sky days These checks involve a side-by-side comparison of the sensor to a sensor of similar design, the calibration of which can be traced to a transfer standard The primary standard pyrheliometer is an instrument selected by an international committee. It was made by Jet Propulsion Lab (JPL) where custody is maintained. If this is not possible, the device should be returned to the manufacturer or to a laboratory with the facilities to check the calibration. The frequency of making comparative readings or having factory calibrations will depend on environmental conditions. Most certainly, any indication of discoloration or peeling of the blackened surface or of scratches on the hemispheres of a pyranometer warrants recalibration and/or service

Net radiometers are more delicate and require more frequent attention than pyranometers Pyranometers of high quality in a clean atmosphere may require recalibration at 2-year intervals, net radiometers should be recalibrated at least yearly. Calibrating the recorder or integrator is an easy task. The standard method involves the use of a precision potentiometer to impress known voltages into the circuit The linearity of the readout instrument may be checked by introducing a series of voltages covering the full scale, checking first up-scale and then downscale. Adjustments should be made as necessary. In the absence of a precision potentiometer, it may be possible to introduce a calibrated millivolt source that covers one or two points. Integrators can be checked the same way, except that the input value must also be timed

2.6.5 *Installation*

Follow the general guidelines set forth in Section 2.2.6, "Preparation for Field Installation." The site selected for an upward-looking pyranometer should be free from any obstruction above the plane of the sensor and should be readily accessible for cleaning and maintenance. It should be located so that no shadows will be cast on the device, so that it is not too close to light-colored walls or other objects likely to reflect sunlight, and so that it is not exposed to artificial radiation sources A flat roof is usually a good choice, but if such a site is not possible, a rigid stand with a horizontal surface some distance from buildings or other obstructions should be used. A site survey of the angular elevation above the plane of the radiometer surface should be made through 360 degrees (The Eppley Laboratory, Inc).

Table 2.6.1. *Classification of Pyranometers According to Physical Response Characteristics*

	Sensitivity (mW/cm^2)	*Temperature (%)*	*Linearity (%)*	*Time Const. (max.)*	*Cosine Resp. (%)*
1st Class	*±0 1*	*±1*	*±1*	*25 s*	*±3.0*
2nd Class	*±0 5*	*±2*	*±2*	*1 m*	*±5.7*
3rd Class	*±1 0*	*±5*	*±3*	*4 m*	*±10*

The same procedures and precautions should be followed for net radiometers that are both upward- and downward-looking. However, the instrument must be supported on an arm extending from a vertical support about 1 m above the ground. Except for net radiometers with heavy-duty domes, which are installed with a desiccant tube in series with the sensor chamber, most other hemispherical net radiometers require the positive pressure of a gas—usually nitrogen—to both maintain the shape of the polyethylene domes and purge the area surrounding the thermopile. In one increasingly popular design, there is a requirement for internal purging with nitrogen and external ventilation with compressed air through holes on the frame. The compressed air supply minimizes fogging and condensation

Precautions must be taken to avoid subjecting radiometers to mechanical shock during installation. They should be installed securely and leveled using the circular spirit level attached to the instrument. Net radiometers are difficult to mount and to maintain free of vibration Pyranometers of the Moll-Gorzynski design, used extensively by Atmospheric Environmental Sciences (AES) of Canada, are oriented so that the emerging leads face north (Figure 2.6.4) This minimizes solar heat on the electrical connections of an instrument that is not temperature compensated. The thermopiles of these instruments should be oriented so that the long side of the thermopile points east and west (Latimer, 1972). The cable used to connect the pyranometer to the readout device, recorder, or integrator should be between 16 and 20 gauge and made of shielded, waterproofed 2-conductor copper wire. The sensor, shield, and readout device should be connected to a common ground Potentiometric millivolt recorders are to be used with most high-impedance, low-signal thermopile radiometers Cable lengths of 300 m or more are practical. Galvanometric recorders can be used with silicon cell radiometers. Soldered, copper-to-copper junctions between instrument connectors and/or cables are essential. Pyranographs or actinographs should be installed on a level surface immune to shadows These instruments should be placed in such a way that the sensitive bimetallic strips lie within 2 degrees of true east and west with the glass inspection window facing north

2.6.6 *Field Operation of a Solar Radiation System*

As part of the quality assurance program, a field calibration check should be performed at least once every 6 months according to the procedures outlined in Section 2 6 4 Solar radiation instruments require almost daily attention. The data should be inspected for a reasonable diurnal pattern and the absence of dark counting Where strip chart or digital printers are used, daily time checks are desirable Data retrieval will depend upon program objectives, but even for climatological programs, data should be collected monthly. All operational activities during a site visit should be logged

2.6.7 *Preventive Maintenance*

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

Should the internal surface of a pyranometer's outer hemisphere become coated with moisture, it can be cleaned by carefully removing the outer hemisphere on a dry day and allowing the air to evaporate the moisture If removal of a hemisphere exposes the thermopile element, extreme care should be taken because it is fragile and easily damaged About once each month, the desiccant installed in most pyranometers should be inspected Whenever the silica gel drying agent is pink or white instead of blue, it should be replaced or rejuvenated by drying it out on a pan in 135°C oven. The level should be checked after each servicing of the radiometer, or at least monthly Significant errors can result from misalignment.

Net radiometers require more frequent maintenance attention than pyranometers. It is necessary to replace the polyethylene domes as often as twice a year or more before the domes become discolored, distorted, or cracked More frequent replacement is necessary in polluted environments due to accelerated degradation of plastic hemispheres when exposed to pollutants A daily maintenance schedule is essential to check on the proper flow of gas in instruments that are inflated and purged with nitrogen. All PM activities should be recorded in a log

2.6.8 *Audit Procedures*

Refer to Section 2 2 4, "Audits," for general guidelines A performance audit on a solar radiation system is only practical with a CTS. The CTS must have the spectral response and exposure equivalent to the instrument being audited One diurnal cycle will establish an estimate of accuracy sufficient for most air quality monitoring applications The method of reporting the data from the monitoring instrument (daily integrated value, hourly integrated value, average intensity per hour, etc) must be used in reducing the data from the CTS to provide a meaningful comparison An audit frequency of at least six months is recommended

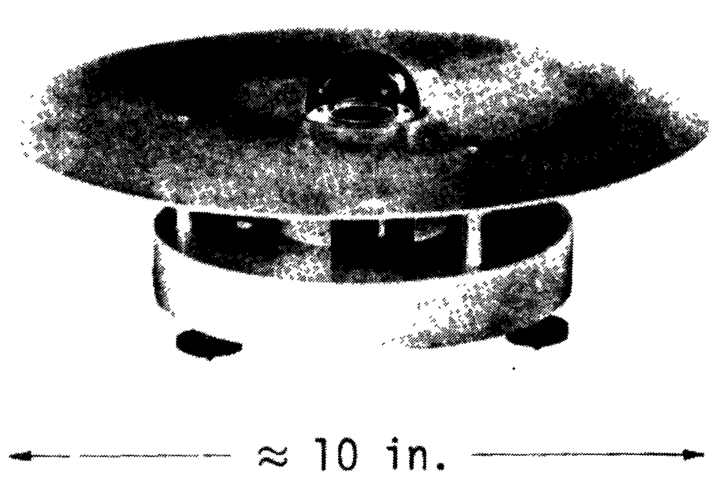

Figure 2.6.4. *A Moll-Gorczynski solarimeter (Department of the Army, 1975)*

2.7 Precipitation Measurements

2.7.1 *Introduction*

By definition, "The total amount of precipitation which reaches the ground in a stated period is expressed as the *depth* to which it would cover a horizontal projection of the earth's surface if there were no loss by evaporation or run-off and if any part of the precipitation falling as snow or ice were melted" (WMO, 1969) In any method of precipitation measurement, the aim should be to obtain a sample that is representative of the fall in the area At the outset, it should be recognized that the extrapolation of precipitation amounts from a single location to represent an entire region is an assumption that is statistically questionable. A network of stations with a density suitable to the investigation is preferable.

Precipitation collectors are of two basic types nonrecording and recording

Nonrecording Gages - In its simplest form, a precipitation gage consists of a cylinder, such as a can with straight sides, closed at one end and open at the other. The depth of the liquid in the can can be measured with a measuring stick calibrated in subdivisions of centimeters or inches (Figure 2 7 1)

To obtain greater resolution, as in the case of the standard 8-inch gage made to NWS Specification No 450.2301, the gage is constructed with a ratio of 10 1 between the area of the outside collectorcylinder and the inside measuring tube. The funnel attached to the collector both directs the precipitation into the tube and minimizes evaporation loss Amounts in excess of two inches of rainfall overflow into the outer can, and all measurements of liquid and melted precipitation are made in the measuring tube with a measuring stick

The automatic wet/dry precipitation collector, available in several designs, represents a specialized nonrecording instrument designed for programs involving the chemical and/or radioactive analysis of precipitation. The collector is built with a sensor that detects the onset and cessation of precipitation and automatically releases a lid to open and cover the collector In one design, the lid can be made to remain open during either wet or dry periods. Another model is made with two collectors, the lid is made to cover one bucket during periods of rain and snow (Figure 2 7 2) In equipment of this kind involving precipitation chemistry, the volume of water in proportion to the constituents collected with the water is important, so evaporation must be kept to a minimum

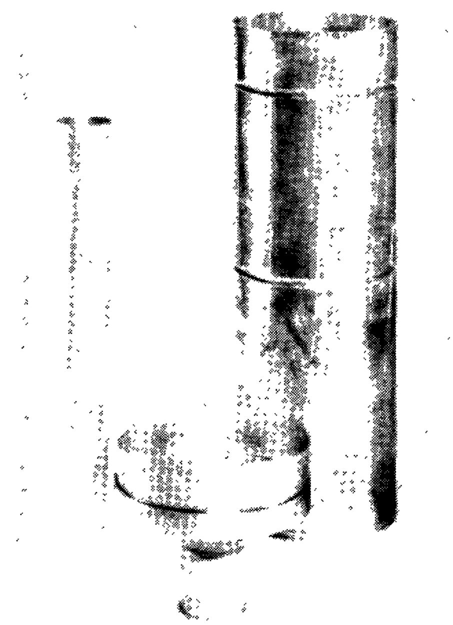

Figure 2.7.1. *A typical standard rain gage (Belfort Instrument Company).*

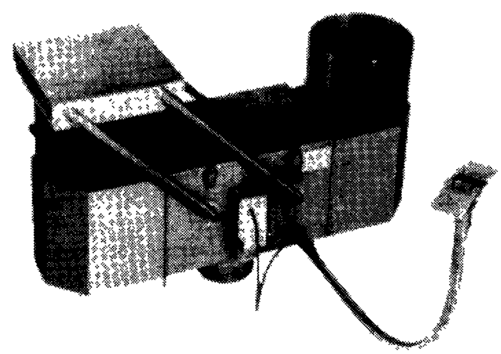

Figure 2.7.2. *Automatic wet/dry precipitation collector.*

Recording Gages - Recording gages are of two basic designs based on their operating principles the weighing-type gage and the tipping bucket-type gage (Figure 2 7 3) The former, when made to NWS Specification No 450.2201, is known as the Universal gage, indicating usage for both liquid and frozen precipitation There are options for the remote transmission of signals from this type of gage The standard National Weather Service Tipping Bucket Rain Gage is designed with a 12-inch collector funnel that directs the precipitation to a small outlet directly over two equal compartments, or buckets, which tilt in sequence with each 0 01 inches of rainfall The motion of the buckets causes a mercury switch closure Normally operated on 6 V d c , the contact closure can be monitored on a visual counter and/or one of several recorders The digital-type impulse can also be used with computer-compatible equipment

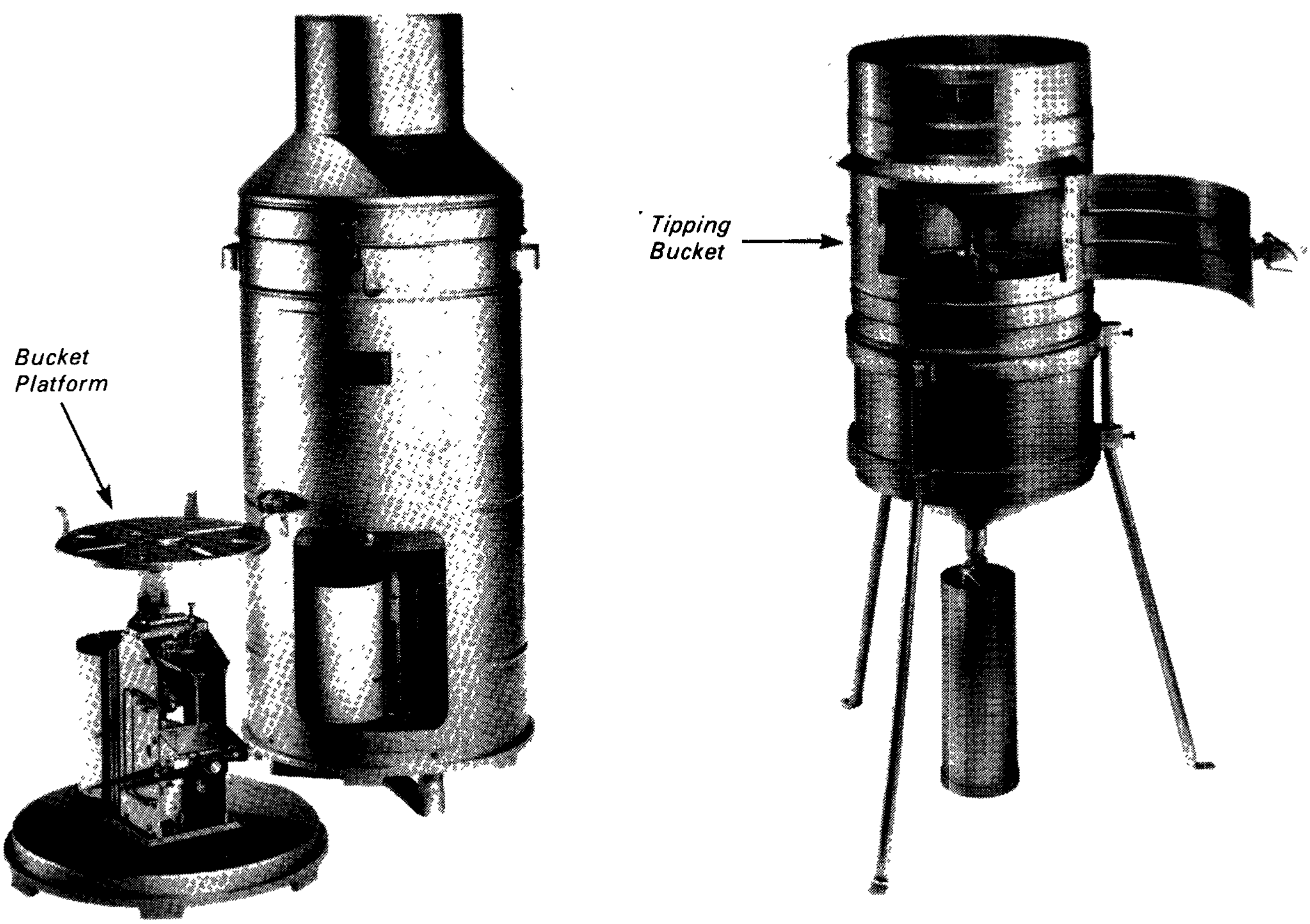

Figure 2.7.3. *A typical weighing rain gage (left) and typical tipping bucket rain gage (Belfort Instrument Company).*

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

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

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

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

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

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

2.7.1 3 Precipitation Data Requirements-In research studies, especially those related to acid rain, the instrument used most frequently is the Automatic Precipitation Collector with one or two collecting buckets and a cover to prevent evaporation In operational activities, the choice is between the weighing gage and the tipping bucket gage For climatological surveys, the choice might include one of the above gages as well as a nonrecording type gage The use of a windshield is recommended to minimize the errors that result from windy conditions if the application requires maximum accuracy

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

2.7.2 *Procurement*

In purchasing a suitable precipitation measuring sytem, follow the general guidelines set forth in Section 2.2 1, "Instrument Procurement " A variety of gages are available commercially In general, the standards established by NWS specifications result in the fewest problems For example, there are numerous 8-inch gages available, but those following NWS specifications are made only of brass and copper, are more durable, and are reported to rupture less frequently under extended freezing conditions than those made of galvanized steel

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

2.7.3 *Acceptance Testing*

Follow the general guidelines advanced in Section 2 2 2, "Acceptance Testing." Except for visual inspection, nonrecording gages do not require acceptance testing. The weighing gages should be assembled and given a quick "bench-top" calibration check using standard weights or a measured volume of water In addition, the clock mechanism supplied with the gage should be checked for at least a couple of days, preferably a week The tipping bucket gage should also be bench tested, primarily to be certain that the bucket mechanism assembly is balanced and that the switch is operational

2.7.4 *Calibration*

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

2.7.5 *Installation*

Follow the general guidelines set forth in Section 2 2 6, "Preparation for Field Installation," and siting guidance described in Section 3.

The support, or base, of any gage must be firmly anchored, preferably on a level surface so that the sides of the gage are vertical and the collector is horizontal The collector can be checked with a carpenter's level placed at two intersecting positions. The level of the bucket assembly on the tipping bucket gage is also critical and should also be checked along its length and width

Once the weighing gage is installed, the silicone fluid should be poured into the damping cylinder as required The pen of the drum recording type is inked to less than capacity because the ink used is hygroscopic and expands with increasing humidity, easily spilling over on the chart. The final calibration check with standard weights or suitable substitute should be made at this time. To check the operation of the tipping bucket, the best approach is to put a known quantity of water in a can with a small hole so that the slow flow can be timed. It may be necessary to adjust the set screws, which act as limits to the travel of the tilting buckets The average of a minimum of ten tips should be used. Adjustment is required if a 10 percent or greater error is found or if greater accuracy is needed.

2.7.6 *Field Operation of a Precipitation Measurement System*

Calibration checks for weighing and tipping bucket gages using the techniques described above are recommended at 6-month intervals Nonrecording gages, whether alone or in a network, should be read daily at a standard time

Although the weighing gage is used for liquid and frozen precipitation, it requires some special attention for winter operations. First, the funnel must be removed when snow is expected Second, the bucket must be charged with an antifreeze, 24 oz of ethylene glycol mixed with 8 oz of oil. The weight of this mixture represents the baseline from which precipitation amounts are to be noted. The bucket should be emptied and recharged when necessary, at about 5 inches in the Universal gage, and at about 10 inches in the punched tape gage All operational activities should be recorded in the station log

2.7.7 *Preventive Maintenance*

Possible leaks in the measuring tube or the overflow container of the gage are easily checked The receptacles are partially filled with water colored with red ink and placed over a piece of newspaper This procedure is especially applicable to the clear plastic 4-inch gage which is more easily damaged Repairs are performed by soldering the 8-inch gage and by applying a solvent to the plastic.

A number of pens, some with greater capacity than others, can be used with the Universal gage All require occasional cleaning, including a good soaking and wiping in a mixture of water and detergent After inking problems, the next source of trouble is the chart drive, but these problems can sometimes be avoided by having the clock drive lubricated for the environmental conditions expected It is a good practice to have spare clocks in stock

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

2.7.8 *Audit Procedures*

Refer to Section 2.2.4, "Audits," for general guidelines. Audits on precipitation measuring systems need be no more frequent than every 6 months. The irregular occurrence of precipitation makes the use of a CTS impractical The performance audit should depend upon the challenging of the gage with amounts of water known to an accuracy of at least 1 percent of the total to be used This method will provide an accuracy of the measurement system but not the collection efficiency of the gage in natural precipitation. For tipping bucket gages use a rate of less than one inch per hour and an amount which will cause a minimum of ten tips.

For weighing gages, it is more convenient to use calibration weights to challenge the weighing mechanism rather than using the gallons of water necessary for full scale testing

Section 3.0
Methods for Judging Suitability of Sensor Siting

3.1 Introduction

Although good instrumentation is a necessity, proper site selection is critical to obtain good meteorological data. It is, from an absolute error point of view, much more important than proper placement of any other kind of air monitoring equipment. Poor placement can and has caused errors of 180° in wind direction, and can cause major errors in any other meteorological variable, including wind speed, temperature, humidity, and solar radiation.

The purpose of this section is to offer guidance in assessing the suitability of meteorological monitoring sites The guidance given is based principally on standards set by the World Meteorological Organization (WMO, 1971) and Federal agencies involved in meteorological data collection (U.S. National Weather Service [NWS] and the Tennessee Valley Authority [TVA, 1977]).

Proper siting is part of the total quality control program. Of course, as in many other monitoring activities, the ideal may not be attainable and, in many urban areas where air quality studies are traditionally done, it will be impossible to find sites that meet all of the siting criteria. In those cases, compromises must be made. The important thing to realize is that the data will be compromised, but not necessarily in a random way It is incumbent upon the agency gathering the data to describe carefully the deficiencies in the site and, if possible, quantify or at least evaluate the probable consequences to the data

3.2 Instrument Siting

The primary objective of instrument siting is to place the instrument in a location where it can make precise measurements that are representative of the general state of the atmosphere in that area. Because most atmospheric properties change dramatically with height and surroundings, certain somewhat arbitrary conventions must be observed so that measurements can be compared. In this section, conventions published by the World Meteorological Organization (WMO, 1971) have been adopted wherever possible

Secondary considerations such as accessibility and security must be taken into account, but should not be allowed to compromise data quality.

3.2.1 *Wind Speed and Direction*

"The standard exposure of wind instruments over level, open terrain is 10 m above the ground" (WMO, 1971). Open terrain is defined as an area where the distance between the instrument and any obstruction is at least ten (10) times the height of that obstruction. An obstruction may be man-made (such as a building) or natural (such as a tree) (Figure 3 2.1).

The wind instrument should be securely mounted on a mast that will not twist, rotate, or sway.

If it is necessary to mount the wind instrument on a roof of a building, it should be mounted high enough to be out of the area in which the air flow is disturbed by the building. This is usually 1 5 times the height of the building. If it is impossible to obtain the proper unobstructed exposure through horizontal relocation of the measurement site, it may be necessary to raise the height of the instrument so that it is out of the wake of the obstruction. This is not a good practice, however, and should only be resorted to when absolutely necessary. Sensor height and its height above obstructions, as well as the character of nearby obstructions, should be documented.

3.2.2 *Temperature and Humidity*

Temperature and humidity sensors should be mounted over a plot of open level ground at least 9 meters in diameter. The ground surface should be covered with short grass or, in areas where grass does not grow, natural earth. The surface must *not* be concrete or asphalt. The standard height for climatological purposes is 1 25 to 2 m, but different heights may frequently be required in air quality studies

The sensors should not be closer to obstructions such as trees and/or buildings than a distance equal to four times their height. They should be at least 30 m from large paved areas and not close to steep slopes, ridges, or hollows. Areas of standing water should also be avoided.

Louvered instrument shelters should be oriented with the door opening toward true north.

3.2.3 *Radiation*

Solar and whole sky radiation measurements should be taken in a location free from any obstruction to the mea-

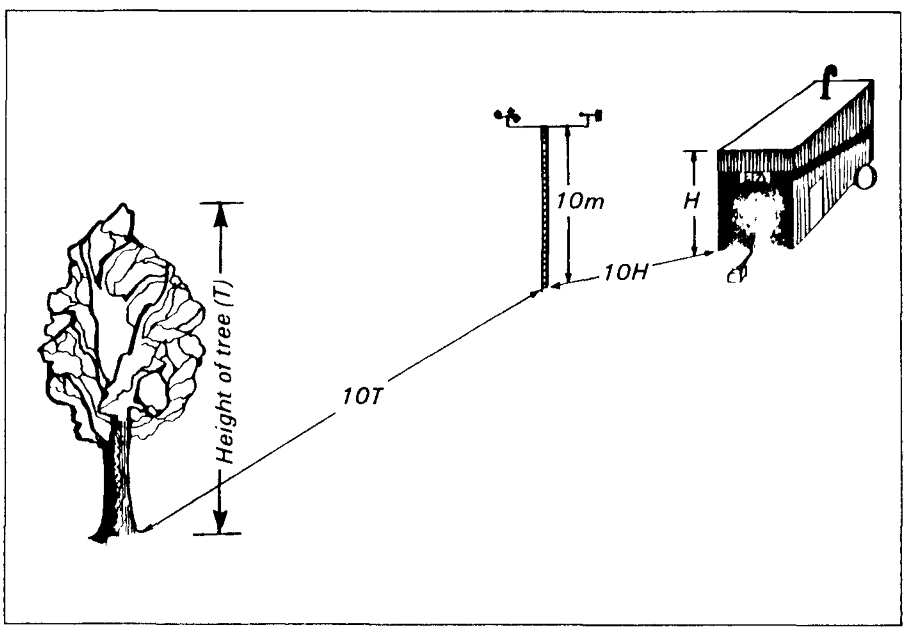

Figure 3.2.1. *Siting wind instruments; a 10-m tower, located at least 10 times the height of obstructions away from those obstructions (not to scale).*

surements. This means there should be nothing above the horizontal plane of the sensing element that would cast a shadow on it. Neither should the instrument be near light colored walls or artificial sources of radiation. Usually a tall platform or roof of a building is the most suitable location.

3.2.4 *Precipitation*

A rain gage should be mounted on level ground so that the mouth or opening is horizontal The gage should be shielded from the wind but not put in an area where there will be excessive turbulence caused by the shield. For example, a good location would be an opening in an orchard or grove of trees where the wind speed near the ground is reduced due to the canopy effect, but a location that is mostly open except for one or two trees would not be good because of the strong eddies that could be set up by the trees. This admittedly requires a good deal of subjective judgment but it cannot be avoided Obstructions to the wind should not be closer than two to four times the obstruction height from the instrument.

In open areas, a wind shield such as that used by the U S National Weather Service should be used.

The ground surface around the rain gage may be natural vegetation or gravel It should not be paved, as this may cause splashing into the gage. The gage should be mounted a minimum of 30 cm above the ground and should be high enough so that it will not be covered by snow.

3.2.5 *Meteorological Towers* It is frequently necessary to measure some meteorological variables at more than one height. For continuous measurements or where the height requirement is not too restrictive, towers may offer the most advantageous measurement platform

Towers should be located in an open level area (see Table 3 2 1) representative of the area under study. In terrain with significant topographic features, different levels of the tower may be under the influence of different meteorological regimes at the same time Such regimes should be well documented

Towers should be of the open grid type of construction, such as is typical of most television and radio broadcast towers. Enclosed towers, stacks, water storage tanks, grain elevators, cooling towers, and similar structures should not be used (Mollo-Christensen, 1979) Towers must be rugged enough so that they may be safely climbed to install and service the instruments Folding or collapsible towers that require the instruments to be serviced or calibrated at the ground are not acceptable because they are usually not rigid enough to ensure that the instruments will be in the proper orientation.

Instruments should be mounted on booms projecting horizontally out from the tower. Wind instruments should be mounted on a boom that will hold it a distance equal to twice the maximum diameter or diagonal of the tower away from the nearest point on the tower. The boom should project into the prevailing wind (e.g., toward the north if the prevailing wind is from the north) if this can be done ambiguously. One may wish to consider having two sets of instruments at each level, located on opposite sides of the tower. A simple automatic switch can choose which set of data to use (NASA, 1968). Documentation of the tower should include the orientation of the booms.

Temperature sensors must be mounted on booms to hold them away from the tower, but a boom length equal to the diameter of the tower is sufficient. Temperature sensors should have downward facing aspirated shields.

The booms must be strong enough so that they will not sway or vibrate excessively in strong winds The best vertical location on the tower for the sensors is at a point with a minimum number of diagonal cross members, and away from major horizontal cross members Even with these precautions, data obtained while the wind blows from the sector transected by the tower may not be free from error

These instrument siting suggestions may seem to preclude the use of many air monitoring sites that otherwise would be desirable, but this need not be the case. In siting air quality monitors that are to be used for long-term trend analysis or large geographic area coverage, it may be perfectly acceptable to have some or all of the meteorological equipment at a different location that better meets the large-scale requirements of the study As long as both sites are in the same area of interest and meet their respective siting criteria, this should present no problems. When the air quality data are to be used for short-term diffusion model validation or studies or short-term levels from specific sources, however, a meteorological station should be located in the vicinity of the air quality sensor.

3.3 Station Siting

Besides care in selecting the local environment of a meteorological sensor, it is important that care be taken in selecting station location with respect to major man-made and topographic features such as cities, mountains, large bodies of water, etc. Meteorological variables are obviously affected by the large-scale surrounding features. The effect of cities has been studied extensively (Ito, 1972; Vukovich, 1971; U S. PHS, 1961). Documented effects include a decrease in an average wind speed, decrease in atmospheric stability, increase in turbulence, increase in temperature, and changes in precipitation patterns. These changes will obviously have an effect on the evaluation and interpretation of meteorological and air quality data taken in an urban area.

Even more pronounced are the effects of large natural features (Slade, 1968) Besides their obvious effect on humidity, oceans and large bodies of water are usually at a different temperature than the nearby land. This generates the well known land- and sea-breezes which, in many coastal areas, dominate the wind patterns. There are also often simultaneous differences in cloud cover between the oceans and nearby land surfaces. This difference in thermal lag, insolation, and changes in surface roughness and vertical temperature structure can have a profound effect on atmospheric stability (SethuRaman, 1974)

The effects of mountains and valleys on meteorological variables and atmospheric dispersion continue to be studied Two of the more interesting recent papers are by Kao (1974) and Hunt (1978). Well-known effects include the channeling of flow up or down a valley, the creation of drainage flow, the

Table 3.2.1. *Limits on Terrain and Obstacles Near Towers*

Distance from tower (m)	*Slope (no greater than) (%)*	*Max. obstruction or vegetation height (m)*
0-15	±2	*0.3*
15-30	±3	*0.5-1 0 (most veg. <0 3)*
30-100	±7	*3.0*
100-300	±11	*10 x ht. must be less than distance to obstruction*

Source. TVA, 1977

establishment of lee-waves, and an increase in mechanically generated turbulence. All of these effects and others can play a major role in the transport and dispersion of pollutants.

The important point is that almost any physical object has an effect upon atmospheric motion. In fact, it is probably impossible to find a site that is completely free from obstruction. This being the case, it is the responsibility of the person choosing a monitoring site to have in mind the various forces at work and to choose a site that will be most representative of the area of interest. If the area is a valley or a sea coast, then the meteorological instruments should be in that valley or near the coast; not on a nearby hilltop or inland 30 km at a more convenient airport site. Of course one must also keep in mind the vertical structure of the atmosphere. Winds measured at the bottom of a 100 m valley will not represent the winds at the top of a 200 m stack whose base happens to be in that valley

The choice of a station for meteorological data collection must be made with a complete understanding of the large-scale geographic area, the sources being investigated, and the potential uses of the data. Then rational, informed choices can be made

Once they are made, the site should be completely documented This should include both small- and large-scale site descriptions, local and topographic maps (1.24,000 scale), photographs of the site (if possible), and a written description of the area that is adequately represented by this site. This last point is most important for it will allow a more rational interpretation of the data. It might state, for example, that a site adequately represents a certain section of a particular valley, the suburban part of a given city, or several rural counties. Whatever it is, the nature of the site should be clearly described in a way that will be clear to those who will be using the data in the future.

Section 4.0
Meteorological Data Validation

4.1 Methods

Once data are collected, they should be reviewed to screen out possible incorrect data points before they are put into accessible storage or passed on to the user. While the purpose of a QA program is to avoid the generation of bad data, it is impossible to do so completely. Even in the best planned and best conducted programs, undetected errors can be generated by faulty equipment, noisy data transmission lines, faulty key punching, and a myriad of other sources Filippov (1968) offers a detailed and thorough discussion of the various possible sources of error

In both automatic (ADP) and manual data screening the most obvious checks should be performed first These include such things as being sure that the data exist and are properly identified, the forms or files are filled out properly, that numbers are in the blocks where they should be, letters are where they should be, and blanks exist where nothing should be This sort of data editing is a subject unto itself and will not be pursued here

Methods of editing or screening meteorological data usually involve comparison of the measured value with some expected value or range of values Techniques for checking the measured value usually fall into one or more of the following categories

1 Comparison with upper and/or lower limit on the allowed range of the data,
2 Comparison with known statistical distribution of the data,
3 Comparison with spatial and/or temporal data fields; and
4 Comparison based upon known physical relationships

A choice must also be made of what to do with the datum that does not pass a validation procedure. Basically there are two choices, eliminate the questionable data from the file, or flag it for further examination. Automatically discarding data may be a viable, cost-effective option if the screening procedure is carefully designed and each datum is not of high value Records must be kept of discarded data so the reason for the fault can be found and corrected Flagged data are examined and a decision made on their acceptability. If unacceptable, it may be possible to correct them or substitute a more reasonable value (Reynolds, 1979) Corrected or substituted values should be so indicated in the data file, with an explanation of the substitution available to the user Alternatively, data of questionable value may be kept in the data file under a flagged status, with a notation of why they are questionable, so that the user can make a decision as to their usefulness This procedure is of questionable value to most users because the collecting agency is frequently in the best position to make a decision on the data

The *range test* is the most common and simplest test Data are checked to see if they fall within specified limits The limits are set ahead of time based usually upon historical data or physically impossible values Some examples of reasonable range tests are rainfall rate greater than 10 in /hour or wind direction not between 1° and 360° In setting the limits, one must take into consideration whether or not the system will select only outrageous, extreme (i e , impossible) values usually caused by data handling errors (such as wind speeds greater than 100 m/s or less than zero) or just unusually high (i.e , possible) values, which should be examined further This may require a further decision on just how extreme a value should be flagged This decision should be based on the real impact of using extreme values should they be in error Considerations of the cost of incorrect data, the possibility of correction or substitution, or replacement by obtaining new data should be made Unfortunately, the decision may also frequently be made on the available resources of those who examine the flagged data

Comparison with known statistical distributions may involve comparison of means, standard deviations, means of extremes, or higher order statistics For example, Lee and Stokes (1978) report that their data base usually had kurtosis of approximately 3 with zero skewness Any of their instruments, then, that showed a marked departure from these values were considered to be in need of further verification (Additional research is needed to determine whether these or similar criteria could be used in other areas)

Lockhart (1979) suggests compressing data into a densely packed graph where long-term (week, month, or seasonal) patterns can be easily seen. Major departures from these subjectively seen patterns can be noted and the data checked Although this method of data verification is usually used to check a particular data set against a longer term climatology, it can also be used to check individual values For example, one might compare a temperature reading with the monthly average maximum or minimum plus or minus (respectively) two or three standard deviations This technique obviously depends on a reliable history or representative measurements being available from the site and is ineffective for noting significant long-term changes in the instrument

Screening data by comparison with fields of similar or related data is commonly done when large amounts of data are taken and when assumptions of spatial continuity of the meteorological variable are physically reasonable The most easily visualized example of this is a field of atmospheric pressure measurements Any value can be compared with those in a large area around it, either visually, or by numerical interpolation Major deviations from the dominant pattern (a low pressure reading in the middle of a high pressure area) are not to be expected Of course, allowance must be made for meso- and micro-scale phenomena such as a shortwave or pressure jump area ahead of a convective storm

Not all meteorological fields can be expected to have the needed continuity Rainfall is a notorious example of discontinuity or microscale variations Wind speed and direction can exhibit continuity on some spatial scales, but care must be taken to account for the many effects, such as topography, that can confuse the issue (See Section 3.)

Interrelated fields can also be used to screen data Rainfall, for example, is unusual without clouds and high humidity while wind direction and speed, especially above the surface layer, are related to pressure gradients

Fields of data in time, rather than space, are also used to check datum points These checks are usually made on rates of change of the data Checks are made both on rates of change that are too high and not high enough For example, atmospheric stability is not expected to change by several classes within an hour A wind direction reading, however, that does not change at all for several hours may indicate that the vane is stuck (assuming the wind speed is not zero) or that there is some other problem with the system.

Screening checks can also be made to assure that physically improbable situations are not reported in the data This kind of check is not commonly used because of the wide variety of conditions that can occur in the atmosphere under extreme conditions. These unusual events would frequently be noted first by some of the statistical or range checks noted above

Some screening points of this type that are used include assuring that the dew point is not greater than the temperature, and that the lapse rate is not greater than the autoconvective lapse rate. Checks on stability class versus time (not allowing "strongly unstable" at night or "stable" during the day) may also be considered in this category.

Table 4.1.1 gives examples of some of the data editing criteria used by three Federal agencies: the National Climatic Center, Klint (1979); the Nuclear Regulatory Commission, Fairobent (1979); and the Tennessee Valley Authority, Reynolds (1978) Examination of the table shows some interesting differences that can be ascribed to the differing missions of the agencies Because of their global concerns, the NCC must allow a far wider range of limits on fields such as temperature and humidity than does an agency with only local interest, such as TVA. On the other hand, the NCC has the data available to do spatial checks over a wider area than would be possible for many local study situations Differences can also be noted depending on the type of data collection (spot readings once per hour or three hours versus continuous recordings) and major interests (synoptic weather patterns versus stability) Filippov (1968) gives an exhaustive review of checks used by weather services of many other countries

4.2 Recommendations

The following is a data validation system recommended for EMSL/RTP to replace the present sytem for screening meteorological data. It could be used to screen data gathered by EMSL, contractors, or state and local agencies. The system takes into account the variable nature of EMSL's field activities. It does not depend on, or have the advantages of, long-term multistation network design, nor is it labor intensive The basic goal is that of rapid identification of field problems, with low value assigned to individual data points, thus allowing the discard of questionable values. Flexibility is available, however, if an individual project's meteorological data are judged to warrant a more criticial approach.

The flow of the system is shown in Figure 4.2.1. All data will go first through a hard copy auditing procedure designed to find data entry and keypunch errors. In the hard copy audit, a percentage of data points will be randomly selected for audit. A second, independent file of these values, as well as the hour just before and after the hour, will be created from the original hard copy This file will be compared with the master file and discrepancies noted. If there are only a few random discrepancies, these points will be eliminated from the system. If there are several, or there seems to be a systematic pattern of errors, the project office (the office responsible for gathering and reducing the data) will be notified so that they can correct and re-enter the data and correct the data entry system.

The data are next passed through a screening program, which is designed to note and flag questionable values. Flagged data will go to the laboratory meteorological office for review There they will either be accepted, discarded, or returned to the project officer if there is a large amount of questionable data. That officer may accept, discard, or correct the data. The screening values are given in Table 4.2 1 They offer a combination of range, rate of change, and physical impossibility checks that are chosen to be reasonably restrictive. It is anticipated that some good data will be flagged, but that most data handling and gross instrument failure problems will be caught.

Data that pass the screening program will go through a comparison program This program will randomly select certain values for manual comparison with information collected by the National Weather Service In the selection process, one day and one hour will be chosen on which data from all stations in the network will be audited One day in every 20 will be randomly chosen, and on that day, one hour between 5 and 9 a m (EST), will be randomly chosen. Data from that hour and day for all stations will be printed out by the audit program for the manual checks. The program will also make compressed time scale plot (20 days of hourly values on one line) for each parameter for the use of the validators.

The data generated by the audit programs will first be compared with National Weather Service data to see if they fit reasonably well with synoptic conditions prevalent in that area The meteorologist will choose the stations to be used in the verification, and train the data clerks in the subjective comparison procedure. All questionable data will be given to the meteorologist for review as above. The variables to be checked in this way will include wind speed and direction, temperature, dew point, pressure, and occurrence of precipitation.

Naturally, if the audit checks show a problem with one or more instruments, an attempt will be made to identify the time range of that problem so that all questionable data can be found. Logs of bad data will also be kept and used to identify troublesome instruments and other problems.

This system is suggested principally for EMSL/RTP, but may prove a useful starting place for state and local air pollution agencies wishing to develop a meteorological data validation procedure. The suggested system is very complete and will be evaluated over a period of time Changes to the system may have to be made, depending upon the needs and resources of the users

Table 4.1.1. *Examples of Data Editing Criteria*

Data are edited or challenged for further review in various systems if the editing criteria are met or exceeded.

Wind speed

$>$25 m/s (NRC)
$>$50 kts (NCC)
$>$20 kts and doubles at next 3-hour observation (NCC)
First 5 hourly values within $\pm$0.2 m/hour of next 4 (TVA)

Wind direction

Any recorded with calm wind speed (NCC)
Same sector for more than 18 hours (NRC)
First 5 within $\pm 0.2^\circ$ of next 4 (TVA)

Temperature

9°F $>$ mean daily maximum for the month (TVA)
9°F $<$ mean daily minimum for the month (TVA)
$\geq 10^\circ$F change in 1 hour at a site (TVA)
First 5 hours within $\pm 0.5^\circ$F of next 4 (TVA)
$>125^\circ$F (NCC)
$<-60^\circ$F (NCC)
$\geq 10^\circ$F change in 1 hour or 20°F change in 3 hours (NCC)
Same temperature 12 or more hours (NRC)

Dew point

Dew point $>$ temperature (TVA, NRC)
Dew point change $> 7^\circ$F in 1 hour (TVA)
First 5 hours within $\pm 0.5^\circ$F of next 4 (TVA)
$>90^\circ$F (NCC)
$<-60^\circ$F (NCC)
Temperature - dew point $> 5^\circ$F during precipitation (NRC)
Temperature = dew point more than 12 consecutive hours (NRC)

Pressure

$>$1060 mb (sea level) (NCC)
$<$940 mb (sea level) (NCC)
Station pressure (inches Hg) + elevation (feet) x 10^{-3} $<$27.75 or $>$31.3 inches Hg (NCC)
Change of 6 mb or 0.2 inch Hg in 3 hours (NCC)

Vertical temperature gradient and stability

$\Delta T/\Delta z > 1^\circ C/100$ m between 10 am and 5 pm (TVA)
$\Delta T/\Delta z < -1^\circ C/100$ m between 6 pm and 5 am (TVA)
$\Delta T/\Delta z > 15^\circ C/100$ m (TVA)
$\Delta T/\Delta z < -3.4^\circ C/100$ m (autoconvective lapse rate) (TVA, NRC)
$\Delta T/\Delta z$ changes sign twice in 3 hours (TVA)

A, B, F, or G stability during precipitation (NRC)
F or G stability during the day (NRC)
A, B, or C stability during the night (NRC)
Change in stability of more than 3 classes between 2 consecutive hours (NRC)
Same stability for $>$12 hours (NRC)

NCC = National Climatic Center (Klint, 1979)
NRC = Nuclear Regulatory Commission (Fairobent, 1979)
TVA = Tennessee Valley Authority (Reynolds, 1978)

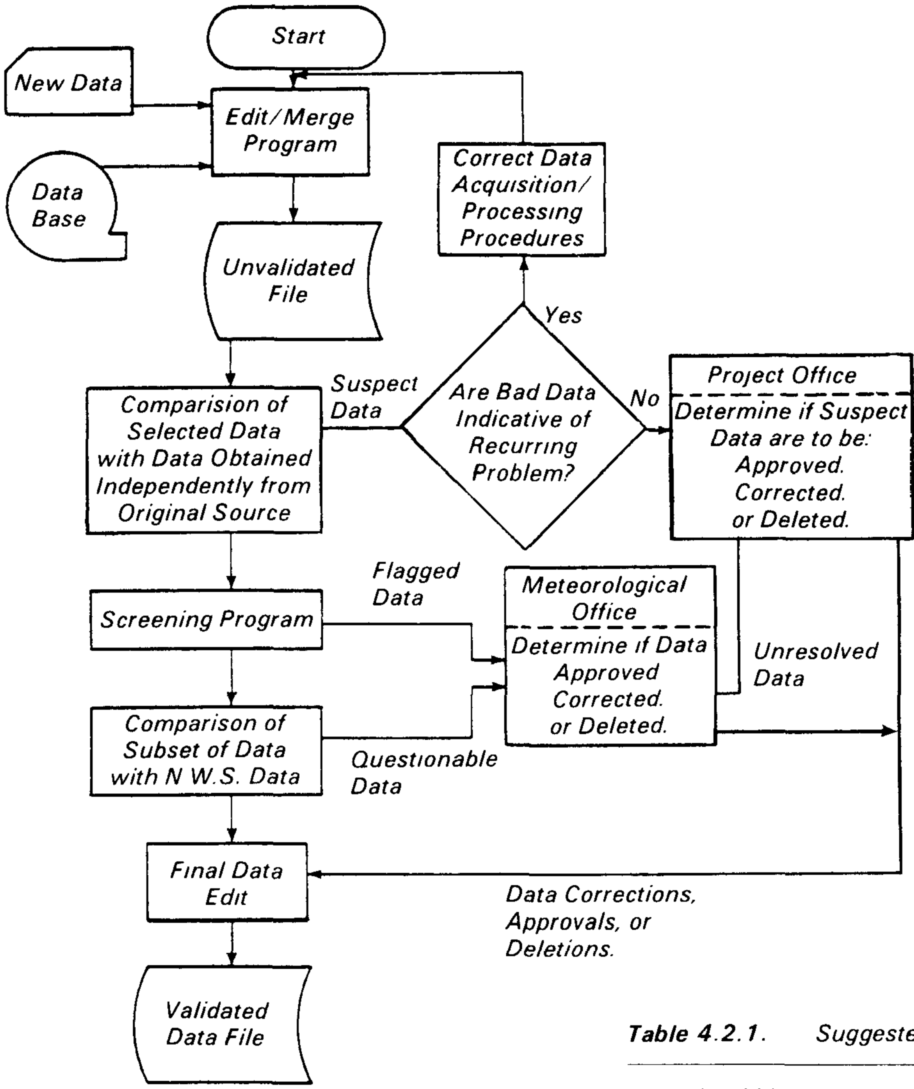

Figure 4.2.1. *Schematic flow of decisions in EMSL data validation scheme.*

Table 4.2.1. *Suggested EMSL Screening Criteria*

Data should be flagged if they meet or exceed the following criteria
Wind speed
>20 m/s (1 hour average)
Unchanged for 12 or more consecutive hours (within ±0.5 m/s)
Wind direction
Any reported with calm or no wind speed
Same 10° sector for 18 or more consecutive hours
Temperature
>45°C
<-35°C
>+5° or <-5° C change/1 hour
Unchanged for 12 or more consecutive hours (within ± 0.5°C)
Dew point
> temperature at that hour (same location)
>+3°C or <-3°C change/1 hour
Unchanged for 12 or more consecutive hours (within 0.5°C)
= temperature for 12 or more consecutive hours (within 0.1°C)
Pressure
>1060 mb (sea level)
<940 mb (sea level)
>+6 or <-6 mb change/3 hours
Rainfall
>15 cm/24 hours
<5 cm/3 months

Section 5.0
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