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Agency

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EPA/600/R-94/038d
March 1995

Quality Assurance Handbook for Air Pollution Measurement Systems

Volume IV: Meteorological Measurements (As Revised March, 1995)

EPA/600/R-94/038d

QUALITY ASSURANCE HANDBOOK
FOR
AIR POLLUTION MEASUREMENT SYSTEMS

Volume IV: METEOROLOGICAL MEASUREMENTS

as revised March 1995

U. S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Atmospheric Research and Exposure Assessment Laboratory
Research Triangle Park, North Carolina 27711

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ACKNOWLEDGEMENTS

This document represents the second revision of the *Quality Assurance Handbook on Air Pollution Measurement Systems, Volume IV: Meteorological Measurements*. This document is essentially the same as its predecessor (EPA-600/4-90-003) but with a new section added on the quality assurance of ground-based remote profilers which include Doppler sodars, Doppler radars, and radio acoustic sounding systems (RASS). In addition, an appendix has also been added on meteorological monitoring guidance for the Photochemical Assessment Monitoring Station (PAMS) network. This edition was critically reviewed by Desmond T. Bailey, Gennaro H. Crescenti, Peter L. Finkelstein, and John E. Gaynor. Special thanks to Robert A. Baxter, Jean-Michel Fage, John S. Irwin, Louis M. Militana, Charles E. Riese, and Kenneth H. Underwood for their comments and suggestions.

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DISCLAIMER

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ATMOSPHERIC RESEARCH AND EXPOSURE ASSESSMENT LABORATORY
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NORTH CAROLINA 27711

November 30, 1989

MEMORANDUM

SUBJECT: QA Handbook for Meteorological Measurements

FROM: Jack Bowen
Project Officer, USEPA, AREAL, QAD (MD-77B),
RTP, NC 27711

TO: Users of QA Handbook for Meteorological Measurements

Enclosed is the final draft of the QA Handbook for Meteorological Measurements. The draft contains some typographical errors, which are shown on the attached errata sheet. These errors will be corrected before the document is sent to NTIS. We decided to send the QA Handbook with an errata sheet attached to those who had requested a copy to prevent any further delays in distribution.

I hope you find this revised edition of the QA Handbook a useful tool in providing practical information and guidance on the operation of your meteorological measurement systems.

If you have any questions, please feel free to contact me by phone (919) 541-3969).

Enclosure

ERRATA SHEET

SECTION	PAGE	PARAGRAPH	LINE	
4.i	1 of 1	3	1	Space between its publication
4.0.0	4 of 5	2	17	Change assume to assumes
4.0.2	1 of 6	4	2	Remove hyphen in consequence
		4	4	Remove hyphen in representative
4.0.4	5 of 7			Table 4.0.4.1 Vegitation to Vegetation
4.1.0	3 of 3	2	1	Change HA to QA
4.1.4	3 of 4	4	3	Change Arizona to Nevada
	3 of 4	5	1	Change t to to
4.1.8	1 of 7	5	1	Change stabalizes to stabilizes
		5	3	Change reagon to region
		5	5	Change validity to validation
	2 of 7	4	5	Change 1 and 360 to 1° and 360°
4.3.0	3 of 3	3	2	Change course to coarse

Section 4.0
GENERAL PROGRAM REQUIREMENTS FOR METEOROLOGICAL MEASUREMENTS
OUTLINE

Section		Pages	Rev.	Date
4.0.0	OUTLINE, PURPOSE AND OVERVIEW OF THE QUALITY ASSURANCE HANDBOOK	5	0	9/89
4.0.1	GLOSSARY	2	0	9/89
4.0.2	STATE OF THE ART	6	0	9/89
	4.0.2.1 AUDITOR SURVEY			
	4.0.2.2 INTERVIEW SUMMARY			
4.0.3	DATA REQUIREMENTS	3	0	9/89
	4.0.3.1 REGULATORY PROGRAMS			
	4.0.3.2 RESEARCH PROGRAMS			
	4.0.3.3 CONTINGENCY PROGRAMS			
4.0.4	MEASUREMENT REQUIREMENTS	7	0	9/89
	4.0.4.1 MEASUREMENT SYSTEM			
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4.0.5	REFERENCES	2	0	9/89

PURPOSE AND OVERVIEW OF THE QUALITY ASSURANCE HANDBOOK

The purpose of this volume of the QA Handbook is to provide information and guidance for both the meteorologist and the non-meteorologist who must make judgments about the validity of data and accuracy of measurement systems. Care has been taken to provide definitions to help those making these judgments to communicate without ambiguity. Methods are described in the handbook which will objectively define the quality of measurements so the non- meteorologist can communicate with the meteorologist or environmental scientist or engineer with precision of meaning.

The first section of the handbook contains a special glossary of terms necessary to meteorology and quality assurance. Following that is an analysis of the state of the art from information and interviews of those practicing QA in the air quality field. The final parts of the first section define some of the requirements for gathering data which a QA effort can compare to the practice of acquiring data.

The second section is devoted to quality assurance and quality control as it is applied to meteorological problems. This section is somewhat independent of the variable being measured. Where the variable is important it is treated individually.

The final six sections are variable-specific. The most important wind measurement is covered in considerable detail. The temperature measurement section concentrates on the temperature difference measurement used for stability determination. The final four sections cover to an adequate depth the measurement of humidity, radiation, precipitation and surface air pressure. Examples are given where possible to help explain the methods and problems to be found in programs of collecting meteorological data and assessing data validity.

The need for common understanding is critical for the practice of quality control (QC) and quality assurance (QA). This is achieved in part by the definitions of the language used within the discipline. From that vocabulary, the details of the systems and procedures are defined in terms of the necessary goals.

There are a variety of QA/QC definitions in the literature and in common usage. Volume I, Section No. 1.3 and Appendix A provide some general definitions. Section 1.4 shows how the elements of QA are distributed and where in the section they are described. The well known "quality assurance wheel" is shown in Figure 1.4.1. The following discussion of definitions is broader based to include meteorological requirements and explicit between QA and QC.

The structure shown in Figure 4.0.0.1 below is from ANSI/ASQC Q90-1987; American National Standard, Quality Management and Quality Assurance Standards Guidelines for Selection and Use. The definitions in the glossary (4.0.1) and the following descriptions are structured to fit Figure 4.0.0.1 and the practices of meteorological measurement.

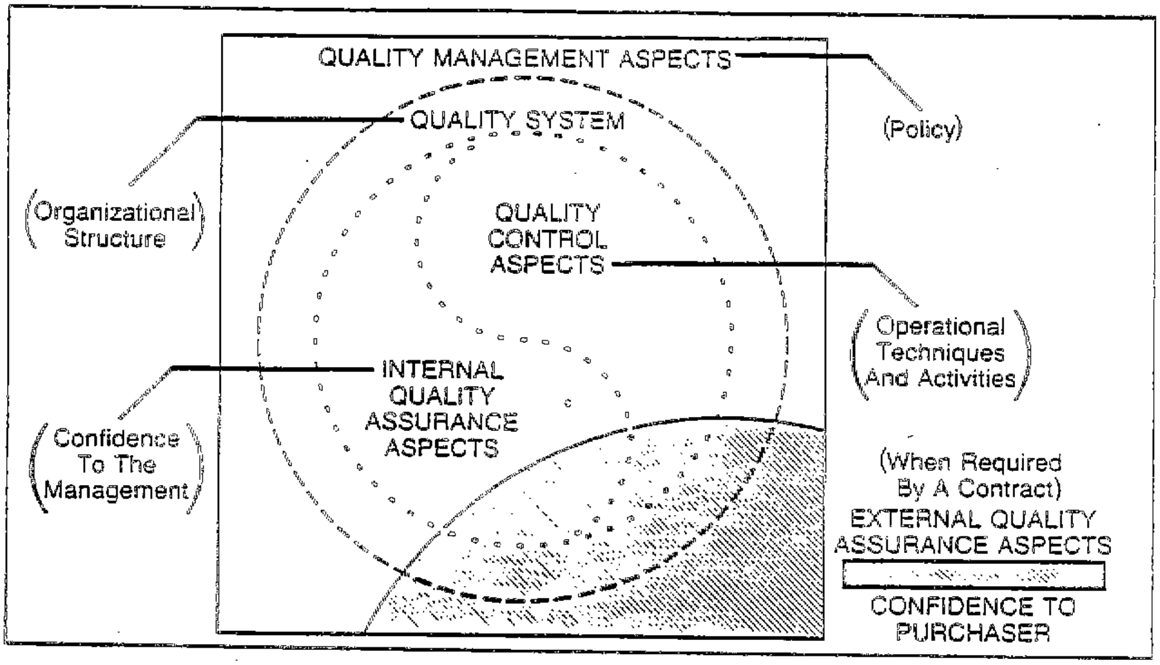

Figure 4.0.0.1 *The Structure of Quality* (reprinted with permission from the American Society for Quality Control)

This figure will be described as it applies to a meteorological company which manufacturers instruments and provides a variety of services. It can also apply to government organizations and temporary project-oriented cooperative organizations. At the top of the figure and the top of any organized effort toward quality are the *QUALITY MANAGEMENT ASPECTS*. These aspects comprise the policy statement for the organization expressed by management. The statement is in writing as a company policy and signed by the president of the company so that there will be no misunderstanding or confusion about the quality goals of instruments so that they do produce valid data. A performance audit, then, is a challenge both to the instrument and to the operator to independently verify that the measurement system is "in control." Just as with system audits, the auditor is primarily a teacher and trainer. The audit method should be the best possible method. The operator should be encouraged to upgrade the calibration methods to do a better job.

Often the operator has no experience with meteorological instruments. Often they are well qualified instrument technicians, but the auditor is an expert, or should be. A mutually valuable goal is for the operator to learn what methods are necessary and most complete and adopt those for the calibration procedure. When the instruments are all working perfectly it is because they are getting the experienced attention it takes for "in control" operation. At this point, the audit becomes a spot checking operation producing documentation from an independent individual verifying this "in control" operation.

If some basic ground rules are followed, the audit is maximized as a learning exercise. One rule is that the operator does all the instrument handling. There is a general reluctance to handle unfamiliar instruments. They might get broken or changed in some mysterious way. The way to become familiar with them is to work with them. The safest environment in which to gain this experience is in the presence of someone who is familiar with the instruments.

Good audit methods are as close to laboratory tests as a field site and the ingenuity of the auditor will allow. This inevitably requires a tower mounted instrument to be taken down, complete with cable or substitute cable, so that tests can be made in a physically convenient environment. For wind sensors, the bearing condition is of vital importance. This can be measured only when the sensor can be connected to the torque instrument with complete control and freedom to move. It is not a proper test to try on a tower or mast. Performance audits, in exactly the same way as calibrations, challenge parts of the system. Ideally, one wants to challenge all of the system, but that is often impossible. Known free atmospheres are not available from NBS. Controlled atmospheres like a wind tunnel or a thermal chamber or a "sun" lamp only challenge a part of the system. They leave out or drastically change the important coupling function. Even controlled atmosphere devices, such as a wind tunnel, are not available to the auditor in the field. All one can do is impose a known condition such as the rate of rotation for an anemometer, and measure the system response. This type of audit assumes that the manufacturer's generic transfer function applies to this sensor, or assume that earlier wind tunnel tests of this sensor still apply (a good assumption if the sensor is not damaged).

Another method is the ASTM collocated transfer standard method. This is the most complete method from the standpoint of total system error sources but it has two drawbacks. First, it is limited to the conditions that prevail during the audit. Secondly, it is very sensitive to exposure or siting bias. It requires careful guidelines pointing out potential bias sources and ways to watch for them in the data. These are covered in the variable-specific sections.

A performance audit program using experienced independent auditors, whether internal or external to the organization, is the first step toward establishing a quality plan if one does not already exist. The goal of the measurement program is to have documented data. The performance audit will point out areas required to get the system "in control." The auditor can help implement the establishment of a quality system, or its key elements, in order to achieve the necessary on-going activities to keep the measurement system "in control" continuously.

The survey which led off the work of revising this handbook exposed some confusion in the community of meteorological auditors with regard to the difference between performance audits and calibrations. A form letter was composed to discuss these differences and to ask for new numbers of audits conducted. The letter used the definitions found in the glossary (4.0.1) and expanded on them with examples. The principal difference is independence of responsibility. Some organizations perceived the documentation of the condition of the system "as found" as a performance audit and the adjustment of the system to acceptable operating conditions, documented "as left," as a calibration. Thus, a single individual could both audit and calibrate during the same visit. By any accepted standard of quality systems definition, this whole process of testing and adjustment is a calibration. This properly documented calibration is the basis for claims of data validity. All the performance audit adds is an independent assurance that the calibrations were thoroughly done and that the documents are complete and accurate. Such assurance must be entirely free of potential influence.

The letter described situations where a single company can be structured to provide both calibration and auditing services, but cautioned that the independence of the auditor requires a management structure insulating the auditor from the budgetary concerns of the operating organization. Responses to this letter were few and in no case was the distinction challenged. All agreed with the concept of independence for QA audits. Regulators should acknowledge the distinction and require true independence.

Situations arise where the fundamental principle of independence between calibration and audit services is difficult to follow. Small agencies may not be able to contract for independent audits. In the interest of documented validity of data for all parties, innovative arrangements among different agencies should be promoted. The individual who operates and calibrates instruments for Agency A might be asked to audit the Agency B instruments in exchange for the operator at Agency B auditing the Agency A instruments. This practice would have the further benefit of stimulating communication about and standardization of good audit methods.

4.0.1 GLOSSARY FOR METEOROLOGY AND QA/QC

ACCURACY - is the degree of agreement of a measurement (or an average of measurements of the same thing), X, with an accepted reference or true value, T, usually expressed as the difference between the two values, X - T, or the difference as a percentage of the reference or true value, 100(X-T)/T, or sometimes expressed as a ratio, X/T.

CALIBRATION - is a *MEASURE* of conformance to or discrepancy from a specification or set of criteria for an instrument or system if necessary and an *ADJUSTMENT* of the instrument or system to conform to the specification or criteria. A calibration may be performed by a person or agency within the operating organization.

DAMPING RATIO (η) - The damping ratio is calculated from the overshoot ratio (Ω). [2]

$$\eta \cong \frac{\ln\left(\frac{1}{\Omega}\right)}{\sqrt{\pi^2 + \left[\ln\left(\frac{1}{\Omega}\right)\right]^2}}$$

DELAY DISTANCE (D) - The distance the air flows past a wind vane during the time it takes the vane to return to 50 percent of the initial displacement. [2]

EXTERNAL QUALITY ASSURANCE - is the activity designed to provide the purchaser with confidence in the quality of what is being purchased.

INTERNAL QUALITY ASSURANCE - is the activity designed to provide management with confidence that the quality system is operating and the management policy is being carried out.

INVERSION (+ΔT) - is the inverted lapse rate or an increase of air temperature with height. There is no general limit for inversion strength.

LAPSE RATE (-ΔT) - is the normal decrease of air temperature with height limited by the auto convection rate of 3.4°C/100 m.

OVERSHOOT (Ω) - The ratio of the amplitude of two successive deflections of a wind vane as it oscillates about the equilibrium position after release from an offset position of ten degrees, as expressed by the equation

$$\Omega = \frac{\theta_{(n+1)}}{\theta_n}$$

where θ_n and $\theta_{(n+1)}$ are the amplitudes of the n and n+1 deflections, respectively.

PERFORMANCE AUDIT - is a report of conformance to or discrepancy from a specification or set of criteria determined by a person or agency separate from and independent of the operating organization.

PRECISION - is the standard deviation of a series of measured values, X_i, about the mean measured value, $\bar{X}$. (see 4.1.5.1)

QUALITY ASSURANCE - All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality. [1]

QUALITY CONTROL - The operational techniques and activities that are used to fulfill requirements for quality. [1]

QUALITY MANAGEMENT - That aspect of the overall management function that determines and implements the quality policy. [1]

QUALITY POLICY - The overall quality intentions and direction of an organization as regards quality, as formally expressed by top management. [1]

QUALITY SYSTEM - The organizational structure, responsibilities, procedures, processes, and resources for implementing quality management. [1]

REPRESENTATIVENESS - is the extent to which a set of measurements taken in a space-time domain reflects the actual conditions in the same or different space-time domain taken on a scale appropriate for a specific application. [4]

STARTING THRESHOLD (S_0, m/s) - The lowest speed at which a vane will turn to within 5° of Θ_S (the true direction) from an initial displacement of 10°. [2]

STARTING THRESHOLD (U_0, m/s) - The lowest speed at which a rotating anemometer starts and continues to turn and produce a measurable signal when mounted in its normal position. [3]

[1] ANSI/ASQC, 1987a: Quality Management and Quality Assurance Standards - Guidelines for Selection and Use. ANSI/ASQC Q90-1987. American Society for Quality Control, Milwaukee, WI 53203.

[2] ASTM, 1985b: Standard Test Method for DETERMINING THE DYNAMIC PERFORMANCE OF A WIND VANE. (Draft 8 of D22.11) Amer. Soc. for Testing and Materials, Philadelphia, PA 19103.

[3] ASTM, 1985a: Standard Test Method for DETERMINING THE PERFORMANCE OF A CUP ANEMOMETER OR PROPELLER ANEMOMETER. (Draft 6 of D22.11) Amer. Soc. for Testing and Materials, Philadelphia, PA 19103.

4.0.2 STATE OF THE ART

The achievement of predicted quality for a product or service can be the delegated responsibility of an identifiable part of an organization. The practice of elevating quality to a management staff level is relatively new. The value of quality control and the umbrella management structure of quality assurance became clear when products, purchased against a specification, were rejected by the purchaser. When the cost of rework or scrap absorbs the profit, an alternative will be found. The alternative is to *do it right the first time* and the path to that goal involves training, in-process inspection, final inspection and all of the other QA functions designed to minimize scrap and rework.

The QA profession grew during World War II and thereafter as the U.S. Government became a significant purchaser using comprehensivespecifications, like the well known Mil-Specs. In the '60sand '70s the practice of planned obsolescence and using the customer as the final inspector set up our industries for failure against foreign competition with higher quality standards. The successful foreign producers, using the quality principles developed in the United States, caused a resurgence of quality awareness.

The Environmental Protection Agency (EPA) recognized the need to set standards, develop standard methods and materials, and produce a system of quality assurance to support validity claims for the data being collected in response to the Clean Air Act. In 1976 a Quality Assurance Handbook for Air Pollution Measurement Systems: Volume I. Principles was published (EPA, 1976). In 1977, Volume II. Ambient Air Specific Methods (EPA, 1977a) and Volume III. Stationary Source Specific Methods (EPA, 1977b) were published. This program addressed the Criteria Pollutants which were covered by federal law. Meteorological measurements were recognized as supportive to the Criteria Pollutant measurement program but they were secondary.

When the Clean Air Act was amended, permission for growth of source strength (and thereby growth of industry) was granted as a con- sequence of diffusion model predictions based on input meteorological data. Now, the law recognized the requirement for valid and represent- ative meteorological data and the need for a structure to provide documented assurance of validity. In 1983, Volume IV. Meteorological Measurements (EPA, 1983) was added to the Handbook family.

Almost all of the QA work provided by the private sector was geared to air and source chemistry. When meteorology was added to the technical requirements list, a variety of solutions were applied by a variety of individuals with a variety of technical backgrounds. The original Volume IV. was like a background guidebook for taking meteorological measurements and general suggestions for how QA and QC might be applied to the requirement for valid data. This revision of Volume IV. is intended to be more specific and more informative and more in the spirit of the other three volumes. It has not, and cannot as yet, specify standard methods. A greater success with predictive models is necessary before knowledge will exist which can dictate the standard methods to assure valid input data. The premise of this Volume IV. is that *measurements worth taking are worth taking right*.

4.0.2.1 Auditor Survey

This handbook is intended to document the methods currently in use in meteorological QA/QC and to point to methods which are optimum for meeting the requirements suggested or defined in various EPA publications. A starting point toward this goal is a survey of all those active in performance and system auditing of meteorological measurement programs. Figure 4.0.2.1 is a copy of the survey form sent to as many people with experience in auditing as could be found. The initial list, shown by company and location in Table 4.0.2.1, grew considerably with help from all the EPA Regions and many state and local agencies. The number of survey forms returned from each company is also shown.

Table 4.0.2.1 - Original Survey List

COMPANY	CITY/STATE	NUMBER
* AeroVironment, Inc.	Monrovia, CA	4
Dames & Moore	Atlanta, GA	2
Desert Research Institute	Reno, NV	2
* Enviro. Monitoring & Services Inc.	Thousand Oaks, CA	1
Environmental Research & Tech.	Fort Collins, CO	1
* Environmental Research & Tech.	Concord, MA	4
Galson Technical Services, Inc.	E. Syracuse, NY	1
Meteorological Standards Inst.	Fox Island, WA	1
Research and Evaluation Assoc.	Chapel Hill, NC	
* Research Triangle Institute	RTP, NC	1
Roy F. Weston, Inc.	West Chester, PA	1
RTP Associates	Denver, CO	1
Technical Environmental Enter.	Aurora, CO	1
Tennessee Valley Authority	Muscle Shoals, AL	1
* TRC Environmental Consultants	E. Hartford, CT	

* indicates companies chosen for in-depth interview

Of the 70 or so forms sent originally or copied and distributed within an organization, 49 forms were returned. The summary of these responses is shown numerically on Figure 4.0.2.1. The number of audits represented by the survey is 12,195, where the definition of an audit is the challenge of one instrument measuring a meteorological variable. Each respondent was asked to qualify himself by specialty, using three or more if necessary but indicating a priority of 1,2 or 3. Some managers reported for their organization of auditors. The responses to the questions were not weighted by numbers of audits. As with most surveys, a few points are useful but action should not be based on the survey results. Of the 49 survey forms returned with data, 21 came from the original list, 9 came from local, state or federal agencies and 19 came from others. Of this 19, 5 came from utilities in the Northeast U.S. (3 from Pennsylvania Power & Light) showing a close relationship to Regional Meteorologists and interest in QA/QC in the area.

Survey of Meteorological Measurement QC/QA People

(please print or type your responses)

NAME________________________ COMPANY________________________

ADDRESS________________________ ADDRESS________________________

________________________ ________________________

________________________ ________________________

PHONE ( ) ( )

I am a __meteorologist, __chemist, __environmental scientist, __QA/QC professional, __instrument technician, __electronics tech., __engineer, __met.tech., __modeler, __manager, __data analyst, __field hand. (use 1,2,3 if you are more than one) This information will be summarized without the use of names or companies or agencies so please be candid.

Consider an audit or challenge as a QA observation of the response of an instrument to a known input and consider a calibration as an OPERATIONAL testing and adjustment, as necessary, of an instrument.

1. If one meteorological audit is defined as a challenge to one variable or one variable of a system, about how many audits have you performed in 1980-1984 ____, 1985 ____, 1986 ____, 1987 ____?
2. Did you 34 usually 7 sometimes 4 never use a written procedure?
3. If a calibration is defined as the testing and adjustment of one variable or one variable in a system, how many calibrations have you performed in 1980-1984 ____, 1985 ____, 1986 ____, 1987 ____?
4. Did you 29 usually 15 sometimes 1 never use the manufacturer's calibration procedure?
5. When you perform an audit, do you require the operator to remove the sensors from their mounted position? 7 Yes 20 No 19 Sometimes
6. Do you require the operator to re-connect the sensor to the system when it is presented for audit? 28 Yes 14 No
7. If 6. is yes, is the re-connection made with 22 the operational cable, 0 a substitute cable or 9 either?
8. Do you 20 usually 11 sometimes 15 never measure the starting torque of each anemometer bearing assembly and transducer?
9. Do you 19 usually 10 sometimes 17 never measure the starting torque of each wind vane bearing assembly and transducer?
10. Do you 9 usually 12 sometimes 27 never use the collocated transfer standard method for auditing a wind instrument?
11. Do you 31 usually 12 sometimes 2 never find the audited instrument meets the required specification?
12. Do you challenge anemometers with known rates of rotation? 33 Yes 12 No - If yes, how many speeds ___? ___Synchronous or ___measured?
13. Do you challenge direction vanes with a dividing wheel? 20 Yes 21 No - If yes, how many angles ___? ___CW, ___CCW, ___both.
14. Will you fill out a more detailed questionaire as a contribution to the quality of this project? 46 Yes 1 No

Figure 4.0.2.1 *Survey Form and Response Summary*

The number of audits, sorted by the technical background rated by the respondent as #1, is shown in Table 4.0.2.2. It is comforting to note that the largest number of auditors consider themselves meteorologists first. While the largest number of audits were reported by persons considering themselves managers first, it is likely that those they managed were distributed like the rest of the group. One organization reported by a manager listed 3,600 audits. It is likely that the discipline of the person doing most of the performance audits is meteorologist.

The information from each question gives some feeling about how the audits reported were conducted. Question 2 shows that 76% of the auditors back their work with a written procedure. Question 4 shows that 64% of the auditors usually use the manufacturer's calibration procedure. This answer pertains to the calibration function which most auditors perform as a separate part of their job.

Table 4.0.2.2 - Survey Summary

		Meteorological Performance Audits				
#1 Specialty	Number	1980-84	1985	1986	1987	Total
Meteorologist	11	1,291	647	473	623	3,034
Engineer	8	253	194	188	206	841
QA/QC	7	387	193	237	318	1,135
Instrument Tech.	5	129	702	102	60	669
Manager	4	2,115	543	551	644	3,853
Environ. Sci.	4	224	70	130	91	515
Electronics Tech.	4	510	165	181	212	1,068
Chemist	3	352	220	256	192	1,020
Data Analyst	1	0	0	0	0	0
No indication	2	0	0	30	30	60
Total	49	5,261	2,102	2,256	2,576	12,195
Average number per year		1,052	2,102	2,256	3,435	
Percent change		-----	100	7	52	

In question 5, 43% of the auditors either do not physically inspect the sensor or do so by performing the operator's function of climbing the tower and removing the sensor. Volume IV. should reduce that percentage to zero. Question 6 suggests that most auditors (67%) do both a physical and an operational challenge of the sensor when it is down from the tower. The conditional question 7 shows a preference for the operational cable (71%) over a substitute cable.

Questions 8 and 9 show only 43% of the auditors usually measure the starting torque of the anemometer and only 41% usually measure the direction vane starting torque. It looks like when an auditor decides to make this measurement, both sensors are included. Several respondents answered "never" but indicated that they were getting equipment to make the measurement in the future. Other auditors inspect the bearing assemblies with educated fingers which tell the auditor whether or not they are "all right" but fail to provide numerical or objective documentation.

Question 10 shows that only 19% rely on the collocated transfer standard (CTS) method for auditing wind instruments. Volume IV. should help increase that number. Question 11 may mean that 70% of the instruments audited are working within specification, or it may mean that the audit methods used are not rigorous enough to find the discrepancies. The fact that half the audits do not include a torque measurement, the only method short of a wind tunnel to challenge starting threshold, points to the latter possibility. Volume IV. should help to improve audit methods toward a standard practice so that this question, asked in the future, will provide an unambiguous answer.

Questions 12 and 13 show a difference in challenging speed and direction. There were 73% of the auditors who indicated the use of a simulated speed to challenge an anemometer. The most common number of speeds was two (52%), followed by three (21%), then one (15%), and finally four or more (12%). There were 86% who indicated a synchronous motor was used. This near unanimity is probably because of the availability of synchronous motors and the lack of availability of simple measurement systems. The measured method is the only choice where good commercial power is not available.

The direction challenges were not as uniform. Of the 23 who indicated the number of angles used, seven said 4, five said 6, four said 8, three said 5, and one each said 1, 12, 16 and 18. There is no consensus there. All but two said they used both clockwise and counterclockwise rotation. The two used clockwise.

If the survey did one thing, it demonstrated the need for guidance toward an acceptable standard of performance auditing. It also demonstrated a recognition of need to move toward that goal and a willingness to help in the process. Only one of 47 said no to question 14.

4.0.2.2 Interview Summary

After the survey results were in, a series of visits was planned to talk to private sector organizations which had a recognized role in quality assurance of meteorological measurements. The first organization visited was AeroVironment, Inc. of Monrovia, California. The half-day discussion with four AV auditors was a frank exchange of methods currently in use, shortcomings of Volume IV and suggestions for the content of the revised Volume IV. The principle of starting torque measurements of anemometer and wind vane shafts as a field substitute for starting threshold wind speed determination in a wind tunnel was accepted. The principle of operators doing all the climbing or handling of sensors was currently practiced.

The second interview was at Environmental Monitoring and Systems, Inc. in Thousand Oaks, California. Half-day discussions with two meteorological auditors reinforced the belief that some organizations were advanced in the practice of meteorological QA. Comprehensively written audit procedures were followed. Questions of the difference between an audit and a calibration were correctly answered with authority. The need for uniform expectations or requirements was expressed in the context of competitive bidding for providing audit services. It was felt that the new Volume IV could help buyers of services to specify a scope of work in enough detail to both assure a comprehensive service and provide a fair bidding competition.

The third interview was with Environmental Research and Technology (now ENSR) in Concord, Massachusetts, perhaps the largest of the five organizations in terms of meteorological services and auditing. Some different concepts and practices were found, particularly in the area of starting threshold determination. Seven meteorologists, field auditors and QA specialists were present during the half-day discussion. This organization was a leader in the field of providing meteorological monitoring services to industry. As a result of the history of providing all services including design, installation, operation, data summarization and QA auditing, an interesting discussion was held on the subject of independence between operators/calibrators and auditors.

The fourth interview was with the head of the field operations department of TRC Environmental Consultants in E. Hartford, Connecticut. This organization was also a leader in providing full meteorological monitoring services. Their procedures developed in a different way. They calibrated their sensors by wind tunnel testing in their calibration facility and employed a regular replacement of sensors in the field. All of the performance auditing related to sensors was done by QA personnel in the calibration facility. This method requires a spare set of sensors be available for each client. The methods described in Volume IV for calibrating or auditing in the field are not necessary if you have a wind tunnel and employ the interchangeable sensor method.

The final interview was with a meteorologist/auditor from the Research Triangle Institute of Research Triangle Park, North Carolina. Since two of the original Volume IV authors were at RTI when the work was written, it was not surprising to find the methods employed to be acceptable standard methods. The level of quality of the field standards used in auditing was the highest, as it was with most of these organizations.

This series of interviews provided valuable insights and confirmations about the best methods to use for meteorological quality assurance practices. It showed the field to be well practiced at the level of the largest and best consulting organizations. The task for Volume IV is to provide a basis for a standard practice in this field at all levels, and to provide a measure by which those practicing in the field can be judged by those with the final authority to accept or reject data on the basis of documented validity.

4.0.3 DATA REQUIREMENTS

There are a variety of reasons why meteorological data are collected. Some reasons relate to regulatory requirements or national monitoring programs. Some data are collected for the purpose of research. Some data are collected against the contingency that they may be needed at some future time. Sometimes data are collected for one reason and then used for other reasons.

The philosophy upon which this volume rests is the belief that data need to have an estimation of uncertainty before the numbers can be dignified by the title "data." The estimation might be a simple declaration such as "The meteorological measurement program was operated in conformance with PSD guidelines." This cites the accuracy requirements for PSD as the uncertainty level for the data and promises that the documentation required for validity claims for a PSD application will be available to back these data. When such an estimation exists and rests on documentation of performance, decisions can be made as to whether or not these data are appropriate for the application.

4.0.3.1 Regulatory Programs

4.0.3.1.1 PSD

The regulatory program used in this document, and to some extent in the On-Site Meteorological Program Guidance for Regulatory Modeling Applications (EPA, 1987b), is the Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD) (EPA, 1987a). This is the most explicit guideline and one requiring a quality of instrument performance available only from sensitive instruments. Recently it seems to be used for other programs as a "standard" of specification.

Most air quality dispersion models described in the Guideline on Air Quality Models (EPA, 1986) used for PSD applications are Gaussian models requiring input data which represent the conditions at the site of interest and which follow a prescribed data content and format. The models require five meteorological inputs. They are:

1) Wind speed - representing the average wind speed at 10 m above the ground (and additional heights for elevated sources) during each hour calculated by a scalar average or mean of samples taken during the hour, usually in 15 minute increments. The samples may be the integrated wind run during the sample period (one or two seconds is often used) or instantaneous samples of speed. A resultant vector magnitude does not represent the initial dilution for which the Gaussian model uses wind speed.

2) Wind direction - representing the average wind direction at 10 m above the ground (and additional heights for elevated sources) during each hour calculated by carefully averaging samples of wind direction or by calculating the resultant vector direction using unity as the wind speed for each sample. A resultant vector direction does not represent the distribution of direction samples which occurred during the hour.

3) Temperature - representing the air temperature at the standard 2 m height above ground (and additional heights for elevated sources).

4) Stability class - representing the site of interest can be estimated by a variety of schemes. Turner (1970) describes a method based on the observation of cloud cover, ceiling height and wind speed along with a known solar elevation angle. Estimations may also be based on the distribution of wind direction (sigma theta) or on the vertical temperature gradient (delta T). Current research is investigating whether or not the Turner method stability class can be estimated with measurements of solar radiation (daytime sky cover substitute) and 2 to 10 m delta temperature (nighttime sky cover substitute) along with wind speed, latitude and date. The method which will be acceptable for the site of interest is determined by the regulatory authority.

5) Mixing height - may be estimated by a method described by Holzworth (1972).

The PSD guideline provides accuracy and performance requirements for wind speed, wind direction, temperature, vertical temperature difference, and solar radiation along with humidity, precipitation and visibility.

Measurements for PSD permitting may, in some cases, be continued after the new source begins to verify the estimations made by modeling. Continued monitoring requires the same QA/QC efforts as the permit phase required.

4.0.3.1.2 Other Programs

Meteorological measurements may be made to augment air quality measurements made to demonstrate compliance with the National Ambient Air Quality Standards (NAAQS) or to monitor trends.

4.0.3.2 Research Programs

Meteorological data networks may be installed for special model validation studies. The same kind of QA/QC efforts are necessary for these programs but they are usually applied on a shorter time scale since the programs are relatively short in duration and the need for documented accuracy could not be greater.

Data representativeness is a critical question as the terrain increases in complexity. Research looks into the number and location of measurement sites and the applicability of certain types of instruments to characterize the complex (turbulent or stratified) air flow systems. Different instruments, such as Doppler sodars for remote vertical sounding, sonic anemometers for small eddy size sensitivity and low threshold speeds, laser anemometers for long path length integration, and even the old standby bivane, are examined to try and optimize the detection of important aspects of flow measurement for model inputs or verification.

Meteorological data are used to find correlations with aerometric measurements in a continuing search for better forecasting capability.

4.0.3.3 Contingency Programs

Industry may choose to monitor meteorological variables at representative sites on their property to document the local air flow conditions in case excessive concentrations are observed which might erroneously be attributed to their source. While such programs may not fall under any regulatory requirements, the use of the data for its contingency purpose requires documentation sufficient to verify the data accuracy.

Other programs may be exploratory to see how on-site data compare with public data from other sites (airports or state or local agency stations). Such questions of representativeness cannot be convincingly answered if the on-site data does not come from suitably sensitive instruments, properly calibrated and maintained and subject to QA/QC effort designed to document data validity.

It is possible to select, install, operate and document on-site measurement systems to meet PSD requirements. Public data from airports may differ from valid on-site data for three reasons. Representativeness deals with different meso-scale structures in the surface layer flow driven, in part, by the larger synoptic flow. It is common to find that airport measurements do not represent other sites just a few miles away because the flow is different. It is also common to find airport data to be different from on-site data because the airport data is essentially an instantaneous sample (a one minute average) taken within ten minutes of the end of the hour while the on-site data for the same hour includes samples from the entire hour. Finally, the airport instruments are selected to serve aviation where low wind speeds are of no importance. Airport instruments do not meet PSD requirements.

4.0.4 MEASUREMENT REQUIREMENTS

4.0.4.1 Measurement System

4.0.4.1.1 Sampling

The usual period of time assigned a data value is an hour. It is getting common to use a shorter intermediate period in the process of generating the hour value. Fifteen minutes is the recommended intermediate period. The fifteen minute values are usually calculated from samples taken during the period. The number of samples is related to the accuracy with which the samples represent the true value for the period. It has been found that when the mean is estimated by 60 samples, the sampling error is 5 to 10 percent. Also, when the standard deviation is estimated by 360 samples, the sampling error is also 5 to 10 percent. For this reason, the required number of samples for sigma theta, the standard deviation of the wind direction is equal or greater than 360 (EPA, 1987b).

If a fifteen minute period is used and if 360 samples are required within that period, a simple calculation shows the maximum time between samples is 2.5 seconds. How a sample is taken and what it represents is also a consideration. If a continuous output voltage is available, as with wind direction, a sample of the voltage can be taken at any time. If the wind speed is calculated by measuring rate of rotation by counting pulses during a fixed time, as is common for systems with the sensor directly connected to a data logger (without a dedicated signal conditioner), the "sample" is really the average for the fixed time. If samples are taken once a second and the anemometer provides three pulses per revolution and the anemometer turns one revolution for every 0.3 meters of air that goes through it, each pulse will represent 0.9 m/s. If samples are taken every 2 seconds, the resolution of the wind speed sample becomes 0.45 m/s. A 15 minute period at 2 second sampling will have 450 samples. The average wind speed will be accurate with a resolution of better than 0.1 m/s. The variance of the wind speed samples may be influenced by the 0.45 m/sresolution of the sample.

Quality assurance considerations should include the determination and documentation of the sampling procedures used in generating the reported hourly data values.

4.0.4.1.2 On-Line Processing

There are two on-line processing programs commonly used in air quality meteorology. One is the program used to combine wind speed and direction samples for an hour. The other is the program used to calculate or estimate sigma theta.

The QA role is to determine what these programs do and judge the suitability of the programs for the measurement application. The field of software QA for meteorology is in it infancy and methods are not standardized as yet.

4.0.4.1.3 Data Handling

There is a need to provide data in certain formats for some applications. If the data are machine processable in the final measurement step, any reconfiguration required will be handled by a program which can be subject to software QA.

If any hand entry work is required, a data handling QC step is required to be sure that errors of transcription do not enter the data base.

4.0.4.2 Documentation.

If there is a requirement to show evidence of data validity, the process of documenting the various QA, QC, and operational activities is important. The added time such documentation takes is usually proportional to the degree of preparation and training which has been applied.

4.0.4.2.1 Station Log

The station log is the journal of all happenings at the measurement site. These include visits where no problems are found, scheduled calibration visits and findings, unscheduled maintenance tests and repairs, and audits. It is a truism that there are never enough field notes to reconstruct with certainty what happened in the past. Planning for the day when such a reconstruction may be necessary can save a long period of data from being discarded because of inadequate documentation.

4.0.4.2.2 Reports

Any activity effecting the measurement system should be reported. This procedure allows responsible individuals to follow these activities without visiting the measurement site or witnessing calibrations and audits. It also provides input to a file of activities related to the system. Reports should include calibrations, audits, discrepancies found and corrected, modifications or upgrades and the like. Reports do not need to be exhaustive or glossy but they do need to be as factual and succinct.

4.0.4.3 Siting and Mounting

4.0.4.3.1 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), the Federal Meteorological Handbook No. 1 (NWS, 1979) and the Tennessee Valley Authority (TVA, 1977). For an understanding of flow around obstacles and their potential bias to wind data, see Hosker (1984).

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.

4.0.4.3.2 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, consistent with the objectives of the data collection program. 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.

4.0.4.3.2.1 Wind Speed and Direction

"The standard exposure of wind instruments over level, open terrain is 10 m above the ground" (WMO, 1971), however optimum measurement height may vary according to data needs. Open terrain is defined as an area where the horizontal 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 4.0.3.1).

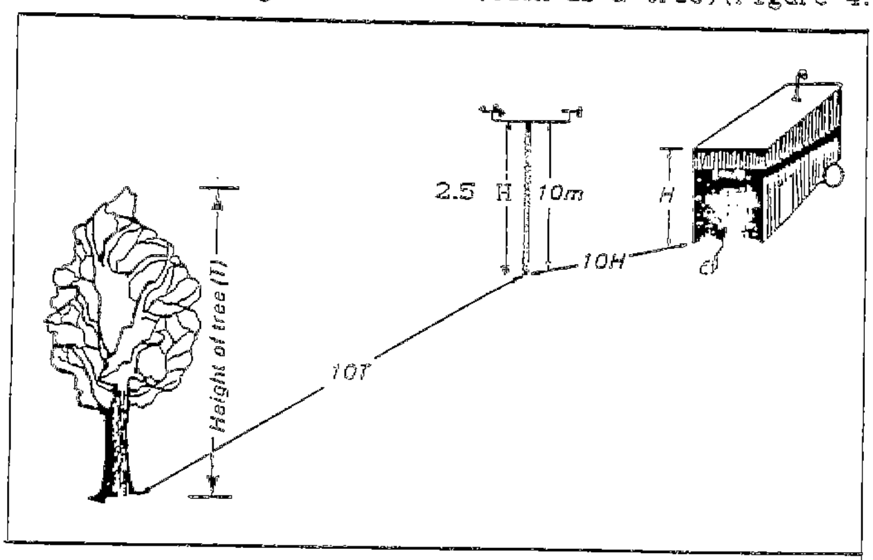

Figure 4.0.4.1 *Siting wind instruments; a 10 m tower located at least 10 times the height of obstructions away from those obstructions (not to scale).*

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 above the roof 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 the obstructions, as well as the character of nearby obstructions, should be documented.

4.0.4.3.2.2 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 non-irrigated or unwatered short grass or, in areas where grass does not grow, natural earth. The surface must not be concrete or asphalt or oil soaked. 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, in the northern hemisphere.

4.0.4.3.2.3 Radiation

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

4.0.4.3.2.4 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 placed 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.

4.0.4.3.2.5 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 4.0.4.1) 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 conditions should be well documented.

Table 4.0.4.1 Limits on Terrain and Obstacles Near Towers

Distance from tower (m)	Slope (between) (%)	Max. obstruction or vegitation 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

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 make the instruments available to be serviced or calibrated at the ground are desirable provided they are sufficiently rigid to hold the instruments in the proper orientation and attitude during normal weather conditions.

Wind instruments should be mounted above the top of the tower or on booms projecting horizontally out from the tower. If a boom is used, it should support the sensor at 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 direction which provides the least distortion for the most important wind direction. For example, a boom mounted to the east of the tower will provide least distortion for north or south winds. 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 of short-term levels from specific sources, however, a meteorological station should be located in the vicinity of the air quality sensor.

4.0.4.3.3 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, 1963). 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 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 clear to those who will be using the data in the future.

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Section 4.1
GENERAL ASPECTS OF QUALITY ASSURANCE FOR METEOROLOGICAL MEASUREMENTS
OUTLINE

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GENERAL ASPECTS OF QUALITY ASSURANCE FOR METEOROLOGICAL MEASUREMENTS
SUMMARY

Quality assurance (QA) for meteorological measurements is a relatively new field. There are generally two reasons for recording meteorological data. One is to *learn* what the atmosphere is doing, particularly the lower part of the boundary layer. The other is to *document* what the atmosphere is doing. It is necessary to find the relevant facts and understand them to learn something . To document what has been learned may require considerably more data and will require some assurance the data are correct. The organizations that need valid data are the ones which collect it, and they will write their own procedures. This is how the National Weather Service has handled data collection for synoptic and climatological applications. When third party requirements with the force of law began to need meteorological data for transport and diffusion modeling and safety analysis, the need for QA was established.

As with most specialties, HA in general has acquired its own language and infrastructure. In this handbook, the goal is to avoid structure which has no specific value to meteorological data validity. On the other hand, the goal is to provide clear definitions, methods and examples which will help produce and verify valid meteorological data. Some of the popular sayings or phrases make valid points. The book "QUALITY IS FREE" (Crabby, 1979) promotes the idea that it is really cheaper to do it right the first time. This concept is easy to demonstrate with manufactured products where bad products will either cost more through warranty repairs or lost sales and bad will. If the "product" is data or services producing data, an awareness of the ultimate cost of the loss of data is important. If no one ever looks at or uses the data, it is a waste of money to buy, install and operate instruments and recording systems. Even a façade of data is not worth the money. If there is a reason for meteorological measurement, that reason will provide the basis for estimating the economic down-side for producing unacceptable data.

Of course data judged "unacceptable" must have been rejected by someone for some reason. The reason for needing the data in the first place will provide the basis for the economic price which must be paid for either not "doing it right the first time" or for fighting the rejection because it was done right. Usually the reason for measuring meteorological variables is a government regulation requirement or a need to combat potential claims of injury. It can be argued that the façade of data coming from the instruments on the tower will satisfy the government regulation requirement. It has been argued that an extra nickel spent measuring meteorological variables (or air quality, for that matter) is a nickel lost to the bottom line profit of a manufacturing plant.

The assumption upon which this handbook rests is that the pertinent government regulations and guidance documents will clearly define what valid data are and how validity is proven. And further, that those people responsible for accepting or using the data will require that the data be valid or rejected. The expertise necessary for this determination will be found in this handbook and its references. This should equally help those who must collect valid data and those who must accept the claim of validity. This assumption clearly moves the purpose for collecting data away from *learning* and into the category of *documenting*. Documentation needs QA.

4.1.1 PLANNING FOR A QUALITY ASSURANCE PROGRAM

A formal quality assurance program should be designed into the monitoring program so that provisions can be made in the measurement system design for necessary quality control checks and for better monitoring of system operations. If these activities are planned and provided for by incorporation of special readouts, calibration equipment, spares, and procedures for their use, then the system is more likely to perform in a satisfactory manner and deliver valid data.

The formal plans for quality assurance are presented in a document called a QA Plan (Lockhart, 1985c and EPA, 1987b). This plan lists all the quality-related procedures and the frequency of their use to document the operation of the instrument system. The QA Plan contains information under different headings to organize all the various activities in a logical sequence and to avoid overlooking an important step. The specifics of each plan must relate to the needs of the program, but the general content elements are the same.

4.1.1.1 Project Description

This introduction establishes why the documentation of meteorological data monitoring is needed and why it is important to the organization that valid data are collected. It also describes how the data will be used which establishes the criteria for judging the representativeness of the data.

4.1.1.2 Project Organization

The literature of QA abounds with examples of the importance of well defined organizational structure starting with the organization policy on quality, endorsed in writing by top management. This provides the authority to "do it right the first time." If the organization has no policy on quality and if someone at the operations level is given the QA responsibility without sufficient authority (often the case), the effort may become just another secondary task which must be done. This is an invitation to a façade system. An organization will seldom build a new plant without the expertise of architects and engineers. Meteorological data systems are often assembled from parts picked from catalogs by experts in other fields who do not understand the routine operating requirements for collecting valid data. A valid QA Plan is a structure to encourage and guide organizations toward a successful collection of needed data.

4.1.1.3 QA Objective

This section is the real QA plan. The first two sections described the project for which the data will be used and the organization of those who will participate in the data collection. This section contains the details of how the QA program will monitor the collection process with the purpose of documenting and defending claims of data validity.

4.1.1.4 Calibration Method and Frequency

Calibrations are tests, and adjustments if necessary, to relate the instrument system to truth or validity. The evidence of this activity, the documentation, is the foundation upon which the judgment of data validity must rest. This section defines in advance how the calibrations will be done, how often and by whom.

4.1.1.5 Data Flow Analysis

This section starts with samples of atmospheric conditions, a rate of rotation of an anemometer representing wind speed for example, and describes how the samples are combined into reported values. The section describes how these values, perhaps hourly averages, are inspected and judged to be acceptable or not. Finally, after validity has been established, the data are archived in some way to become available for use as the project requires. An experienced meteorologist reading this section will know what the data mean and what data quality control has been applied.

4.1.1.6 Validation and Reporting Methods

Section 4.1.1.4 provides points in time at which the instrument performance is known. This section describes what criteria are used for any automatic data inspection programs applied between calibrations and how the results of such programs are implemented and reported. If comparisons are made to other similar measurements, such as a wind speed at a different location or a different time, this section will document the methodology applied.

4.1.1.7 Audits - Performance and System Types

Audits may be required or chosen to add to the documentation some independent evidence of the performance of the meteorological instruments and/or the performance of those who are responsible for implementation of the QA Plan. This section defines how often performance audits are used to challenge the measurement instrument system and how often system audits are used to challenge the implementation of the QA Plan or program. Also defined is the type of auditor to be used. Internal auditors are members of the organization who are independent from those responsible for collecting and handling the data. External auditors are usually outside contractors. In either case, the auditor must be experienced in the field of meteorology and must be provided support from the operating organization. Auditing should be the most positive learning experience for operators and a contributor to data validity.

4.1.1.8 Preventive Maintenance

Some instruments require routine service to assure valid data. Solar radiation sensors have glass covers which need to be properly cleaned on some schedule (daily or weekly), depending on its location. Tipping bucket raingages need to be checked periodically for spiders or other insects which might take up residence in the bucket mechanism. Anemometers and wind vanes have bearings which will need service (usually replacement) on some time scale (quarterly or annually), depending on the environment. Some dew point sensors require coating periodically. All such predictable service points should be recognized and a preventive maintenance plan described for each of them in this section.

4.1.1.9 QA Procedures

Section 4.1.1.2 describes the QA objectives. This section contains the details of how these objectives will be met. A written procedure will both document how the QA task will be addressed and guide a QA person through the process. Procedures are a mechanism for establishing technically correct methodology which can be followed by people without the technical background or experience to write the procedure. While it is not practical to use experts to perform routine tasks, it is necessary to have the expert guidance to follow. Procedures fill this need. Procedures should be controlled to the degree that they cannot be changed without written approval of an expert. A system audit checks to see if procedures are being followed as they are written.

4.1.1.10 Corrective Action and Reports

Documentation is the main goal of a QA Plan. General procedures will require noting in the Site Log any activity relating to the meteorological system. Top management, having established the policy and granted the authority to "do it right the first time," needs to be aware of the QA activities required by the QA Plan. If a procedure or inspection uncovers a discrepancy with respect to the clearly written system specifications, a discrepancy report becomes the message to initiate corrective action. Top management needs to see these reports along with the corrective action statements (usually a part of the discrepancy report form) to know that the system is in control. Too often, problems must be visible to top management if corrective action to the system is going to be initiated. Audit reports and other performance reports are circulated and followed up by procedures described in this section of the QA Plan.

4.1.2 ORGANIZATION OF AUTHORITY AND RESPONSIBILITY

Quality does not mean the best money can buy. It means that the customer gets what he needs and expects, no more and no less. The way to assure a quality product or service is to first set a top management policy in writing stating that goal or commitment. The implementation of such a policy requires a person who can avoid the conflict of interest of providing the product or service and judging its quality before it is delivered. This usually means a Quality Assurance Manager. Once the policy is set and the QA Manager is chosen the procedures by which quality is assured can be written, usually a QA manual. The manual might proclaim that every project with a deliverable product or service will have a QA Plan.

The authority to establish this kind of organizational structure must be top management. During the establishment period, top management must participate and approve the quality organizational structure and procedures. Once established, top management can delegate authority to the QA Manager for operating the department. A routine feedback from the QA Manager to top management is necessary to preserve the control of delegated authority, see that it is being used effectively and demonstrate to the rest of the organization a level of importance placed on the quality policy.

Once the organization is in place, and QA Plans are required, the job of collecting wind data for a PSD (Prevention of Significant Deterioration) application starts with a QA Plan. What are the measurement requirements? How will the data be handled? How will the instruments be calibrated and serviced? What procedures will be used? What outside authority will assure management that the QA Plan is adequate? Once all the steps required to gather a year of valid wind data have been defined, the QA people will monitor the process, help train inexperienced operators, and build a documentation base to support the claim of validity for the data once the year is over. This should include some outside auditing to add to the documentation an impartial expert opinion of satisfactory performance, or bring to the attention of the QA people and their management any problems which might have been overlooked. The best time for an independent audit is at the beginning of the data-taking period when the loss of valuable time can be minimized.

The principles of this approach to quality are sound and irrefutable. The cost is less than any other approach. All that is required is to figure out, in sufficient detail, what and how the job is to be done before it begins and to specify how the job will be monitored to assure satisfactory completion. Anything less is a gamble which may or may not pay off. Most organizations do not like to gamble, but many do.

4.1.3 QUALITY CONTROL GUIDELINES

Quality control is a process which operates in parallel with the production of a product or a service. There is a gigantic body of literature on the subject. Some examples of books are Juran (1979), Feigenbaum (1961) and Grant and Leavenworth (1974). A technical organization, the American Society For Quality Control (ASQC) exists for the promotion of quality systems. ASQC has committees of volunteers to establish guidelines and standards for the quality profession. One such committee is the American National Standards Institute Accredited Standards Committee (ANSI ASC) Z-1 Committee on Quality Assurance. A product of this committee is a series of standards (ANSI/ASQC 1987a-e) in which is stated the need to qualify quality control with an adjective describing what is to be controlled. This need is nowhere greater than in meteorological monitoring.

In the meteorological literature there are recent papers (Wade, 1987 and Lockhart, 1988) in which the use of quality control is discussed. There is a difficulty with the language used to describe a task and the perception of control as related to those working the task. Assume the task is the accumulation of a one year data set of wind and temperature measurements. The QA Plan describes the goals and the specifications to which the instruments must conform. Purchasing has bought the instruments with a purchase order requiring conformance to performance specifications and describing how the conformance will be tested. A suitable site has been found and a consensus has been reached as to the representativeness of the site. Receiving inspectors accepted the instruments and operators have installed them. The QA Plan called for an independent performance audit at the beginning of the data year which the system passed. The QA Plan calls for an inspection of the data on a weekly basis by the meteorologist or environmental scientist who will be working with the data. The QA Plan provides a procedure with which the data inspector can communicate in writing with the operators to report questionable data and receive an answer of special instrument checks. The QA Plan requires operators to calibrate the instruments on a six month frequency or when problems are found. The QA Plan specifies how the calibrations are to be done and to whom the reports will be routed. At the end of the year the data are summarized and made ready for use in diffusion models. Where is control and where is quality control?

The whole program is controlled by the top management through the QA Plan. How well the various parts of the organization carry out their responsibilities is checked on by the QA people or person. If the receiving inspectors balk at performing their service because they are too busy, top management participates in the decision to either modify the QA Plan and Policy on Quality or find a way to accomplish the receiving inspection. Management may choose to gamble that the instruments are all right and any problems will be uncovered during the installation and audit. This is management's prerogative and this gamble is a pretty safe one. Without the QA Plan the manager of receiving may make the decision without the benefit of knowing what the stakes of the gamble might be. While the whole project is controlled by the QA Plan, there is one data quality control function performed by the meteorologist/environmental scientist; on a weekly basis the data are examined and accepted or rejected. If problems or questions arise, discrepancy reports will be initiated which operate in accordance with the QA Plan. The inspector finds that the wind direction looks too steady and writes it up. The operator goes to the site and, finding that the vane has been removed by a predatory bird, installs a spare, notes the action in the site log and on the discrepancy report, recalibrates if necessary, and reports back to the inspector closing the loop. This is a true quality control activity. The quality of the data is being controlled by the experienced judgment of the data inspector who looks back in the data to find when the vane disappeared, and deletes or flags the data as missing.

Another quality control function is the periodic calibration. This is an instrument quality control process where adjustments are made as necessary to keep the instruments "in control." If more frequent calibrations are used or if the program goes on for several years, a standard control chart may be used to visually track the "in control" status of the instruments. The data quality control inspector must see the calibration reports and contribute to the decision about what if anything to do to the data as a result of calibration findings. Doing anything to the data requires very careful consideration and thorough documentation.

When the organization policy is to achieve the level of quality the "customer" expects, the whole organization effectively becomes a part of the QA department. Various techniques, such a quality circles, may be used to maintain a high level of quality through broad participation and training. These techniques also underscore the management's dedication to the quality policy. It is only when other criteria, such as departmental profit goals, enjoy a higher priority than does quality that an independent "watch dog" organization is required to achieve a published quality policy. The price for quality is inversely proportional to its place on the priority scale. When quality is first on the list, the most efficient and least expensive process can be found for its achievement.

4.1.4 TRACEABILITY PROTOCOL

There is a general practice in QA/QC to use a hierarchy of standards resting on international standards or those maintained by the National Bureau of Standards (NBS). This results in claims of calibrations that are "traceable to NBS." While it is difficult to define traceability in quantitative terms, there is value in using an authority against which other instruments can be compared. This section will discuss how this hierarchy relates to meteorological measurements.

Most meteorological measurements contain some sensing element which reacts to the variable of interest and the usual transducer outputs of voltage, current or frequency.. In terms of accuracy, the response of the sensing element is the most important and the most difficult to define (see sub-section 2, Specifications, for each variable). The measurement of the various components of the electrical output, including digital code, is straight forward and subject to normal methods of calibration and certification. Protocols for "traceability to NBS" for voltage will be discussed first.

4.1.4.1 Voltage

Regular calibration labs maintain transfer standards which are sent to NBS for calibration. These in turn are used to calibrate the lab's voltage sources which in turn are used to calibrate a subject volt meter. This process has gone on for years and is called "traceable to NBS." Calibration labs check a volt meter, adjust it if necessary, and affix a calibration sticker certifying the meter to be in calibration at the date tested and recommending re-certification at a future date (six months to a year). This traditional process is entirely acceptable.

Manufacturers of volt meters also have transfer standards which they use to calibrate and certify their products. Modern digital volt meters or volt-ohm meters (DVOM) are very stable in calibration, particularly those of high quality. Another method for achieving "traceability to NBS" involves the comparison of DVOMs. If one DVOM is certified as accurate, either by a calibration lab or by the manufacturer with a transfer standard, and another DVOM is placed in parallel across a voltage source, the uncertified one can be certified by that comparison. This process is valuable to use in performance auditing in order to fix the accuracy with which the operator calibrates the signal conditioners. The process yields a relative accuracy if neither DVOM is certified, but it becomes absolute as comparisons are made with certified DVOMs.

What is an acceptable error in voltage measurement for meteorological purposes? Assume a measurement system with a full scale output of 1 volt for wind speed, wind direction and temperature difference. Assume the DVOMs are on a range displaying millivolts where the 1 volt full scale looks like 1.000. How important is it if the two DVOMs disagree by as much as 0.002 volts? If the range for wind speed is 0.2 to 50 m/s, and the accuracy requirement is 0.2 m/s, what is that accuracy requirement expressed in volts?

$$50.0 \text{ m/s} = 1.000 \text{ V}$$
$$0.2 \text{ m/s} = 0.2/50 \times 1.000 = 0.004 \text{ V}$$

The disagreement between the DVOMs is equivalent to half the accuracy requirement. For all practical purposes a disagreement of this size is not important, but an auditor would like more information. Is it a bias or a random difference?

A good DVOM, like the Fluke 8060A, specifies its accuracy on the 2.0000 V range as ± (0.04% of reading + 2 digits). On the 20.000 V range the accuracy is specified as ± (0.05% of reading + 2 digits). If the two DVOMs were on the same output of 0.1000 V (5 m/s for the wind speed example), and if they were on a range equivalent to the 2 V range stated above, they should each read 0.1000 ±(0.00004 + 0.0002) or between 0.09976 V and 0.10024 V. Truncation of the measurement to fit the display would cause the meters to read between 0.0997 and 0.1002 which would be interpreted as 4.98 and 5.01 m/s. If the difference were as much as 2 mV (0.1 m/s), it would indicate a bias (calibration) error in one or both of the DVOMs. If the DVOMs were each on a 20 V range, they should read 0.100 ± (0.00005 + 0.002) or between 0.09795 V and 0.10205 V. Truncation would force the meters to read between 0.097 and 0.102 which would be interpreted as 4.85 and 5.10 m/s. A difference of 2 mV (0.1 m/s) in the meter readings could be either a bias error or a random error from the 2-digit uncertainty. Switching both DVOMs to the 2 V range would resolve the question.

Table 4.1.4.1 summarizes the accuracy of the conversion of the transducer output to voltage output in units of voltage and units of meteorology for the 1 volt range example for wind speed,direction and temperature difference.

Table 4.1.4.1 - Voltage vs. Met. Unit Accuracy

Variable	Range		Accuracy (0.1% FS)	
	Volts	Met. Units	Volts	Met. Units
Wind speed	0.000 - 1.000	0.0 - 50.0 m/s	0.001	0.05 m/s
Direction	0.000 - 1.000	360 - 360 deg.	0.001	0.36 deg.
Δ T	0.000 - 1.000	-5.0 - 15.0 °C	0.001	0.02 °C

4.1.4.2 Wind Speed

Traceability to NBS has some meaning in the measurement of wind speed. The National Bureau of Standards Fluid Mechanics Section operates a pair of calibration wind tunnels at their facility in Gaithersburg, MD (Washington, D.C.). One can arrange to send an anemometer to NBS for calibration. A report will result which describes the output of the sensor or system (rate of rotation or volts) at a series of wind speeds. NBS states the accuracy of the wind speed they use to be 0.1 mph. How the user implements the test report is a different story (see 4.2.12). If the user is a manufacturer, the test report will probably be smoothed by some least square method which predicts speed from rate of rotation. The speed predicted by the rate of rotation of the anemometer calibrated by NBS will then be transferred to another anemometer by collocating them in another wind tunnel or by calibrating the wind tunnel as an intermediate standard. If new anemometers agree with this transfer of the performance of the "standard" anemometer to within some margin of error, the calibration of the new anemometer is said to be "traceable to NBS."

There is no standard wind. NBS uses a structure designed to smoothly control the air being driven by a propeller-motor assembly. How smoothly and uniformly the air flows through the test section is determined by testing. The wind speed at some point in the test section is calculated from the measured pressure difference between the pitot tube and the static pressure, correcting for air density. The pressure difference is measured with a manometer. Anyone can build a wind tunnel and measure its performance as accurately as can NBS. "Traceable to NBS" provides a relative standard of comparison with absolute errors which are small compared to the needs of the scientific and industrial users.

4.1.4.3 Wind Direction

"Traceable to NBS" has no meaning as it relates to wind direction (see 4.2.2.2).

4.1.4.4 Temperatureand Temperature Gradients

There is a hierarchy for temperature much the same as voltage. Calibration labs and manufacturers maintain sensors with calibrations run by NBS. A user can send an electrical transducer, which has a unique relationship between resistance and temperature, to a calibration lab and get a report on that relationship as determined by the lab's transfer standard. This calibration is called "traceable to NBS" because the transfer standard was calibrated there. Some concern about how the subject transducer and the transfer standard are exposed to the "same" temperature is warranted. The test method and test facilities are not usually certified by NBS and so the calibration may not deserve the inferred NBS authority.

Differential temperature is nothing more than two or more temperature measurements taken at different points. The important calibration for this variable is one which compares one instrument to the other, a relativecalibration. Traceability is not relevant to relative calibrations.

4.1.4.5 Solar Radiation

Traceability to an absolute measurement of solar radiation is achieved by collocated comparisons with secondary standards at organizations such as the Desert Research Laboratory in Arizona or at a scheduled World Meteorological Organization (WMO) inter comparison. An absolute measurement of the intensity of the direct beam from the sun is made with an Active Cavity Radiometer. This instrument is based on fundamental principles. The cavity "sees" only the direct radiation from the sun. The optically black surface in the cavity is heated by radiation of all wave lengths. The cavity temperature is accurately measured and the instrument yields the absolute flux of direct radiation (D) at the measurement location. A global pyranometer with a disc located to shield the direct beams from the disc of the sun measures the diffuse radiation (d). With knowledge of the angle of the sun from the zenith (θ), the total global radiation (G) can be calculated by the following formula.

$$G = D \cos \theta + d$$

Secondary standards, traceable to such an inter comparison, may be used t calibrate operational pyranometers. Pyranometers which have been calibrated in this way may be used as collocated transfer standards in the field.

4.1.4.6 Atmospheric Water Vapor

It is possible to create an absolute humidity and NBS has a facility for doing just that. Atmospheric water vapor instruments, expressing the conditions as relative humidity or dew point temperature can be calibrated by NBS in a fundamental procedure requiring only the measurement of length (volume), mass and temperature. There are standard methods for creating relative humidity environments useful for some kinds of instruments. ASTM (1985c) describes such a method. For air quality applications, a collocated comparison provides adequate accuracy. If the collocated instrument is a psychrometer and proper methods are used (ASTM, 1984) for measuring the wet- and dry-bulb temperatures, traceability to NBS might be claimed for the thermometers used in the psychrometer.

4.1.4.7 Precipitation

There are some measurements where traceability to NBS is possible but not required. Precipitation measurement is essentially a measure of the volume of liquid water (including the liquid water equivalent volume of snow) which is collected by an area bounded by a cylinder. Calibration may require volumes of water or equivalent weights. The accuracy required and expected from precipitation gages will be well served by the accuracy of commercial measuring equipment. Ordinary chemical dispensers such as graduated cylinders and burets are accurate enough without calibration traceable to NBS. The measurement of the area of the cylinder may be made with a commercial ruler or tape, always keeping in mind the need for quality commercial products for the best accuracy without extraordinary effort.

4.1.4.8 Atmospheric Pressure

Calibration labs create pressures with devices using weights. It is possible to use weights with calibration traceable to NBS, but the accuracy with which the atmospheric pressure is needed for air quality applications does not require such an effort.

4.1.5 ESTIMATING PRECISION AND ACCURACY

4.1.5.1 Definitions

There are about as many definitions of precision and accuracy as there are bodies devoted to carefully defining these terms. The definition used here is found in EPA (1976) on page A17 as follows:

"Accuracy - The degree of agreement of a measurement (or an average of measurements of the same thing), X, with an accepted reference or true value, T, usually expressed as the difference between the two values, X - T, or the difference as a percentage of the reference or true value, 100(X-T)/T, and sometimes expressed as the ratio, X/T."

For meteorological purposes, this concept of accuracy is acceptable. The problem comes from knowing the "accepted reference or true value." Section 4.1.4 Traceability Protocol discusses this problem for all the meteorological variables of interest. All data that are used are averages or means. The formula for accuracy is

$$\bar{E} = \frac{1}{n}\sum_{i=1}^{n}(X_i - T) = \bar{X} - T \qquad (1)$$

where

$\bar{E}$ is the average error (accuracy)

X_i is the ith sample of X

T is the non-varying true value of X

n is the number of samples

i is a sample, 1,2,3...n

Accuracy, the average error, or really the uncertainty in the value, X_i, has two or three components. They are bias, conditional bias, and random error, a statistical expression of a series of which is called precision. Since, in some cases, bias and conditional bias can be separated, both will be discussed.

Precision is defined in EPA (1976) as "A measure of mutual agreement among individual measurements of the same property, usually under prescribed similar conditions. Precision is most desirably expressed in terms of the standard deviation but can be expressed in terms of variance, range, or other statistic. Various measures of precision exist depending upon the 'prescribed similar conditions.'" This is more difficult to fit to meteorological measurements made in the atmosphere because "prescribed similar conditions" are hard to find. Parts of the instrument system can be challenged by controlled environments such as wind tunnels and temperature, humidity or pressure chambers. The precision of the measurement can be found, providing it is larger than the variability of the controlled environment. Usually it is not larger and what is measured is the variability of the controlled environment. The definition to be used in this handbook is as follows:

Precision is the standard deviation of a series or measured values, X_i, about the mean measured value, $\bar{\bar{X}}$. The formula for an estimation of the precision or standard deviation, s, is

$$s = \pm \sqrt{\frac{\sum_{i=1}^{n} (X_i - \bar{\bar{X}})^2}{n - 1}} \qquad (2)$$

An equivalent formula which can be used for real-time calculations in modern data loggers or computers (Juran, 1979, p 22-7) is

$$s = \pm \sqrt{\frac{n \sum_{i=1}^{n} (X_i^2) - \left(\sum_{i=1}^{n} X_i \right)^2}{n\ (n - 1)}} \qquad (3)$$

Equation (3) is preferred because it introduces only two rounding errors rather than the four introduced in equation (2). Suppose $X_i' = X_i + C$ where C is some constant value. Then

$$X_i = X_i' - C \quad \text{and} \quad \bar{\bar{X}} = \bar{\bar{X}}' - C \quad \text{and} \quad X_i - \bar{\bar{X}} = X_i' - \bar{\bar{X}}'.$$

Therefore, the standard deviation, s, of a series of values, as calculated by (2) or (3) is identical to the standard deviation, s, of the same series of numbers, each plus a constant. If the true value, T, is constant, the precision of the accuracy estimate, $\bar{\bar{E}}$, is identical to the standard deviation of the samples, X_i.

Bias is defined in EPA (1976) as "A systematic (consistent) error in the test results." It goes on with qualifiers which apply to chemical labs. For meteorology, the definition for this handbook is simply the average difference between the measured value X_i and the true value T_i, $\overline{(X_i - T_i)}$. Using the symbols of ASTM (1984), the systematic difference (d) or bias is found from the following equation.

$$d = \frac{1}{n} \sum_{i=1}^{n} (X_i - T_i) = \bar{X} - \bar{T} \qquad (4)$$

where

T_i is the ith sample of the true value of T

It can be seen in these definitions that when the true value, T, does not change, the accuracy is the same as the bias. What is the precision of formula (1)? For the non-varying true value, the accuracy with which any sample may be determined is

$$E_i = \bar{E} \pm s \qquad (5)$$

and for a variable T

$$E_i = d \pm s \qquad (6)$$

When T varies, X may vary in a systematic way. For example, the case for wind direction found in 4.2.2.2.2.3 shows a systematic difference, d, of -3.4 deg. (orientation error) and a conditional bias (potentiometer linearity error) of about ± 0.5 deg. on some wave shape with an amplitude of about ± 2 deg. The accuracy of the vane might be stated as

$E_i = -3.4 \pm 2.5$ deg. or, removing the orientation error, $E_i = 0.0 \pm 2.5$ deg. or, correcting for linearity at each angle, $E_i = 0.0 \pm 0.5$ deg. There is little point in making this final correction in operational programs. This is just an example of how a conditional bias can be treated to decrease an error or improve the accuracy.

4.1.5.2 Collocated Transfer Standards

If a collocated transfer standard (CTS) is used to estimate accuracy, any correction which makes the CTS provide values closer to the true value is worth making. The statistical method of operational comparability (ASTM, 1984) is used when a CTS is employed to estimate the accuracy of an instrument operating in the field. The analysis requires differences between the instrument being challenged and the CTS, properly sited. The differences are best if the same data logger can sample the challenged sensor, X_a, at the same time as the CTS, X_b, so that the difference, $(X_{ai}-X_{bi})$, can be stored, squared and accumulated. If this is not possible, the CTS data logger should form averages over the same time period as the averages formed in the challenged system. Then these averages are used for X_{ai} and X_{bi}. The first calculation to make is comparability from the following formula:

$$C = \pm \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_{ai} - X_{bi})^2} \qquad (7)$$

where

X_{ai} is the ith measurement of the subject output

X_{bi} is the ith simultaneous sample from the CTS

The systematic difference, d, is calculated from (4) substituting X_{ai} and X_{bi} for X_i and T_i, respectively. The estimated standard deviation of the difference, s, is calculated from (8).

$$s = \pm \sqrt{C^2 - d^2} \qquad (8)$$

The minimum sample size, n_o, required for the calculation of C is given by equation (9). Most data loggers sample sequentially. The time between members of a data pair to satisfy the requirement of simultaneous measurements must not exceed one tenth the response time of the instruments. The time between pairs of measurements must be greater than four times the response time of the instruments to assure sample independence.

$$n_o = \left(\frac{3s}{r}\right)^2 \qquad (9)$$

where

r is one increment of resolution reported by X_a

For example, a CTS wind vane operating in a speed range of 2 to 7 m/s with a delay distance of 2 m would have a response time between 1 and 0.3 s. If a data logger had an analog to digital conversion cycling time faster than 0.03 s and if samples were taken no faster than every 4 s, and if the resolution (measurement and display) of the measuring system were 1 deg., and assuming a 5 deg. standard deviation of the difference, s, the minimum sample size would be

$$n_o = \left(\frac{3 \times 5}{1}\right)^2 = 225 \text{ samples, requiring 15 minutes @ 1 per 4 s.}$$

There cannot be too many samples. The minimum is specified for a confidence of 99.7% or greater that the estimated mean difference, d, is within one element of resolution (1 deg. in the example). At that confidence level, the accuracy of the estimate increases (error decreases) as the square root of the sample size. If the sample size were increased by a factor of 4 to 900, the accuracy of the estimate would by 0.5 deg. The values of C and d found from a series of differences are only valid for the range of conditions used for the test. The shorter the period of time that is sampled the smaller the range of conditions will be. A reasonable goal for a minimum CTS time period is 24 hours from the standpoint of dynamic range variation.

Assume the CTS will provide the true value in a test in the free atmosphere within the limits of the calibration of the CTS to some other standard, typically 0.1 m/s with respect to some wind tunnel for speed and 1 deg. with respect to TRUE NORTH for average direction. The accuracy of the challenged instrument is the comparability, C. The bias, d, provides the calibration and orientation error. The standard deviation, s, provides the irreducible random error or minimum functional precision with which two instruments measuring the same quantity report when operated using the ASTM D4430-84, determines the operational comparability of meteorological measurements. Lockhart (1989) found the following values of s for wind speed and wind direction:

Wind speed ---------------- s ≅ 0.2 m/s

Wind direction ------------- s ≅ 2 deg.

When s is found to be larger than these values, the assumption must be made that either site bias or a malfunctioning sensor is at fault. Under those conditions the calibration error, d, is also suspect.

4.1.5.3 Other Considerations

The average error, $\bar{E}$, calculated over a uniform distribution of X, is the same as the average difference or bias. The contribution of the standard deviation of the difference between X and T (or the precision error) goes to zero and the average accuracy is the bias. The measurement of meteorological variables in the atmosphere is never really that simple.

Occasionally there is confusion between the word precision and the resolution of the measurement system. Resolution is the fineness of the measurement system, the output of the measurement system or the display of the output of the measurement system. A wire-wound potentiometer in a wind direction sensor may have a resolution of 0.355 degrees (1,000 windings of a wire over 355 degrees). The circuit that converts the resistance of the potentiometer to voltage may have a resolution of 0.1 degree. The display or recorded value may show whole degrees. The whole degree may be truncated from the output or rounded. For example, if the potentiometer wiper is at the 312th wire (312 x 0.355 = 110.76 degrees), the voltage output (312/1000 x 1 volt = 0.3120 volts) has no resolution; the resolution of its measurement is limited only by the resolution of the volt meter. If the system has a digital output with a resolution of one degree, the output will be 110 degrees (truncated) or 111 degrees (rounded). The resolution of the sensor in this example is 0.36 degrees and the resolution of the system is 1 degree.

A wind direction system with a resolution of 10 degrees might have a precision of ± 0.5 deg. (it would take a lot of samples to prove that precision). On the other hand, a wind direction system with a resolution of 0.1 deg. might have a precision of ± 3 deg. (because of hysteresis in the coupling of the potentiometer to the vane in the sensor). Resolution should be specified to match the needs of the data application and to provide sufficient information for data QC.

Most of the discussion in this handbook includes the sensor and signal conditioner providing an output. Good digital data systems degrade the output so little that they contribute only a small error to the total. The resolution and accuracy example 4.1.4.1 applies to any digital system. There is a two digit uncertainty in the digit which represents the resolution of the measurement. If the analog to digital converter resolves wind direction to 10 deg., the accuracy cannot be better than ± 10 deg. If the converter resolves to 1 deg., rounds to the nearest 10 deg. and displays 10 deg., the accuracy of the average direction may be 3 deg. while the accuracy of a single observation is ± 5 deg.

When analog recorders are used, their error must be added to the error of the measurement. For some recorders this error can get quite large. Seldom considered or specified, for analog recorders which use rolls of chart paper, is the error caused by expansion and contraction of the paper as a function of temperature and humidity. This error added to the resolution uncertainty of narrow paper rolls marked by a tapping bar (when such recorders are used) can dominate the error of the system when the analog recorder data are used as measurement data.

Random errors identified for each component of a system can be combined to estimate the total system error by the RSS (root sum square) method. Biases or systematic errors cannot be combined in this way. They must be added arithmetically. See Fritschen and Gay (1979) for further discussion of error analysis.

4.1.6 SYSTEM AUDITS

A system audit, as defined in EPA (1976, p A10) is "A systematic on-site qualitative review of facilities, equipment, training, procedures, record-keeping, validation, and reporting aspects of a total (quality assurance) system, to arrive at a measure of the capability and ability of the system. Even though each element of the system audit is qualitative in nature, the evaluation of each element and the total may be quantified and scored on some subjective basis." In short, it is an evaluation of the suitability and effectiveness of a QA Plan or QA Manual.

Any audit is most useful when considered as a learning or training exercise. Given the newness of the implementation of quality systems to air quality programs, particularly meteorology, a mechanism for "on the job training" is useful. Given the two facts that everyone really wants to do a good job and almost everyone is a stranger to the concepts of structured quality systems, an audit is a valuable tool. There is really little difference between air quality and meteorology when it comes to system audit principles. The short section on system audits in EPA (1976) is slanted toward air chemistry projects. In a very general way, a system audit should include the following elements for any technical discipline.

1. Declared Agenda - The audit should not be a surprise or contain surprises. The serious audit is well planned in advance in writing. The items to be covered are spelled out. The agenda is structured with the help of those to be audited, recognizing the areas where they may need special help.

2. Entry and Exit Interview with Top Management - A short introduction meeting with the authority being audited sets the stage for the cooperation necessary for success. Success is defined as improving the audited program through training and education. A short exit interview will announce the findings already discussed with the QA people being audited. The exit interview and the audit report should contain no surprises.

3. Checklist Structure - The audit should flow along a prepared checklist of questions, but if time is limited as it usually is, flexibility is valuable. Special problems, either found or volunteered should be resolved even at the expense of failure to finish the checklist.

4. Audit Report - The report should be delivered in a timely manner, certainly no more than 30 days after the audit, preferably within a week of the audit. The report is the important documentation verifying the QA program is "in control." It must contain the structure for corrective action with plans and schedules committed in writing. An open-loop pledge or a general plan is likely to get a low priority. The value of the audit and corrective action must be clear to the audited organization if the system audit is to be something other than a paperwork exercise.

5. Follow-up - The QA Plan of the organization being audited should require some form of documentation of the completion of the tasks defined in the corrective action plan. Completion of this task closes the loop for the system audit.

A short visit to understand the organization, QA Plans and Procedures, and to meet the QA person is a good first step. It is difficult to do an effective system audit without access to all three.

Since there is a large spectrum of quality programs which might be audited, it is important to keep in mind the original reason for the audit and the objectives and regulations defining the quality program. One objective must be to provide the necessary level of quality at the minimum cost as well as to make the audit process useful and effective. The goal is to ensure valid data with documentation backing up the claim for validity. This can happen in many different ways, some of which may not conform to the auditor's concept of a system. It is not the role of the auditor to redesign the system, but to determine if the system meets the objectives and requirements.

4.1.7 PERFORMANCE AUDITS

This handbook will concentrate on performance audits. The audit methods for each variable will be described in each of the variable-specific sections. The purpose of a performance audit is to determine as completely as possible whether or not the instruments are producing valid data. It is the responsibility of the operators to calibrate and operate the instruments so that they do produce valid data. As mentioned in Section 4.0.0, performance audit methods may be identical to those used in calibration. If they are different, it is expected that the audit method is most comprehensive challenging the greatest part of the total system. A complete calibration of an anemometer requires a wind tunnel. Most operators do not have access to a wind tunnel and elect to use the manufacturer's wind tunnel experience as authority for the anemometer transfer function. This practice is generally acceptable where manufacturers can provide test reports confirming their results. Statistics on the distribution of error of samples of production run anemometers with respect to the generic transfer function are necessary if the manufacturer does not calibrate each unit during manufacture. If 100% calibration is a part of manufacturing process, the method of calibration should be available from the manufacturer.

A performance audit may include a challenge by a collocated transfer standard. Such data serve to check the transfer function at a few points. The uncertainty of the challenge is usually greater than wind tunnel challenges where the conditions can be carefully controlled.

A performance audit on variables such as relative humidity (or dew point temperature), solar radiation and atmospheric pressure will usually include a collocated transfer standard comparison. This is may be the only way a challenge can be made to the whole measurement system.

4.1.8 DATA VALIDATION PROTOCOL

4.1.8.1 Strip Charts

Some years ago, meteorological data were recorded primarily on strip charts. Average values were estimated by "reading" the charts. The most common and the most useful strip chart was one where the output of the measuring system was continuously recorded by means of a galvanometer movement or a servomotor. Data QC meteorologists became expert in determining the validity of the data by examining the strip chart trace, a process necessary while checking the digitizing of the strip chart data.

When the digital data logger and computer first appeared, it was the recommended practice to have strip chart recorders in parallel to the digital systems. The strip chart data could be "read" and used to fill the gaps when the digital system failed, a common occurance in early designs. Many meteorologists found that the strip chart data contained information which was not present in the digital listing. The most important information was the character of the output during the period of time that the digital system was sampling and averaging. One example is the presence and frequency of potentiometer noise in the wind direction output. This information is an early indicator of potentiometer failure. Whether or not the digital average was influenced by this noise could be seen by the comparison of the two outputs, the strip chart being used as truth.

Another example shows threshold degradation by the character of the anemometer trace. Of course the effect of ice or freezing temperatures on anemometers and wind vanes could often be seen on the strip chart. The digital average value would simply be a number which met the plausibility test but was erroneous.

Digital systems have become more reliable, accurate and capable of on-line processing and at the same time less and less expensive. The economy of the digital system pushed the analog recorder to a "back up" role and toward extinction. Digital systems show promise of both large memory sufficient to save one second data samples for time history plots and on-line diagnostic programs to monitor output patterns for unrealistic variability or lack thereof.

Until the technology stabalizes enough to allow a consensus to be developed and regulatory positions to be taken, requirements for strip chart data will be a reagon or agency specific requirement. The one clear fact is that strip chart data, used as a data quality control tool, will result in a better data validity protocol.

4.1.8.2 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.

4.1.8.2.1 Comparison with known distributions

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.

4.1.8.2.2 Comparison with other data fields

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 4.0.4.3.2.4).

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.

4.1.8.2.3 Comparison based on physical relationships

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.

Table 4.1.8.1 Examples of Data Editing Criteria

Wind Speed:	>25 m/s (NRC) >50 kts (NCC) >20 kts and doubles at 3-hour observation (NCC) First 5 hourly values <±0.2 mph of next 4 (TVA)
Wind Direction:	Any recorded calm wind speed (NCC) Same sector for more than 18 hours (NRC) First 5 hourly values <± 2° of the next 4 (TVA)
Delta Temperature:	$\Delta T/\Delta z$ >1°C/100m between 10 a.m. and 5 p.m. (TVA) $\Delta T/\Delta z$ <-1°C/100m between 6 p.m. and 5 a.m. (TVA) $\Delta T/\Delta z$ >15°C/100m (TVA) $\Delta T/\Delta z$ <-3.4°C/100m (autoconvective)(TVA)(NRC) $\Delta T/\Delta z$ changes sign twice in 3 hours (TVA)
Stability:	A,B,F, or G stability during precip. (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 class for >12 hours (NRC)
Temperature:	9°F > mean daily maximum for the month (TVA) 9°F < mean daily minimum for the month (TVA) > 10°F change in 1 hour at a site (TVA) First 5 hours within ±0.5°F of next 4 (TVA) >125°F (NCC) <-60°F (NCC) > 10°F change 1 hour or 20°F in 3 hours (NCC)
Dew Point:	Dew point > temperature (TVA)(NRC) Dew point change >7°F in 1 hour (TVA) First 5 hours within ±0.5°F of next 4 (TVA) >90°F (NCC) <-60°F (NCC) Temp. - dew point >5°F during precip. (NRC) Temp. = dew point >12 consecutive hours (NRC)
Pressure:	>1060 mb (sea level) (NCC) <940 mb (sea level) (NCC) Change of 6 mb or 0.2 inch Hg in 3 hours (NCC)

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 4.1.8.1 gives examples of some of the data editing criteria used by three Federal agencies: the National Climatic Center (NCC, now NCDC), Klint (1979); the Nuclear Regulatory Commission (NRC), Fairobent (1979); and the Tennessee Valley Authority (TVA), 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. The criteria listed in the table are used to identify data to be edited or challenged for further review.

4.1.8.3 The AREAL System

On the following page is a data validation system recommended for AREAL to replace the present system for screening meteorological data. It could be used to screen data gathered by AREAL, contractors, or state and local agencies. The system takes into account the variable nature of AREAL'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 critical approach.

The flow of the system is shown in Figure 4.1.8.1. 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 4.1.8.1. 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.

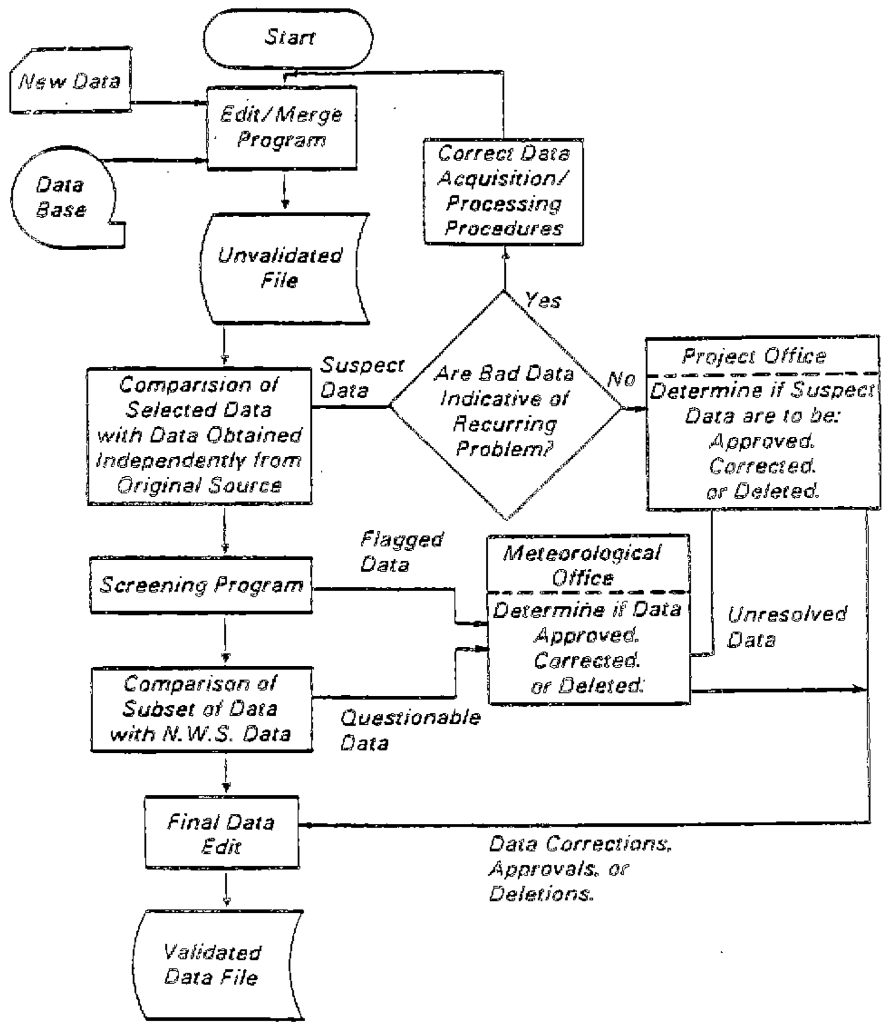

Figure 4.1.8.1 *Schematic flow of decisions in the AREAL data validation scheme.*

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 AREAL, 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.

4.1.9 QA REPORTS AND CORRECTIVE ACTION

4.1.9.1 Operations Log and Maintenance Reports

In all of section 4.1 it has been stressed that the real purpose for a QA or Quality program is to document data validity and the steps taken to make that determination. Any activity which has the potential of affecting the validity of the data must be reported. A report usually includes a note in the station log indicating the time of the operator visit and visual status of the sensors. The log is signed by the operator. If the operator found a problem which he was authorized to fix, the log would contain the entry to that effect. If the operator is not authorized to make the repair or does not have the necessary parts, a maintenance report can initiate the work and the purchase of the parts to fix the instrument. When parts are changed, serial numbers or property numbers should be noted in the log. If a part does not have a number (some cup assemblies and propellers do not have numbers), a number of some sort should be assigned and marked on the part with permanent ink. The QA Plan should provide some communication route and method by which the person responsible for the project and the person responsible for data quality control (if they are different people) are notified of work done on the system.

4.1.9.2 Calibration Reports

Calibration reports are the most crucial documents of a data collection project. They are the foundation blocks which uphold the the validity claim. Quality Control and the routine inspection of the data spans the time between calibrations. The calibration reports will show whether or not the system is "in control." If the system is always "in control" or operating within the required tolerance limits stated in the QA Plan and generated by the application, and the data QC does not have any unsolved mysteries, the data are valid. If the calibration shows problems, the report will also show the corrective action taken or initiated. The "as-found" and "as-left" readings are a vital part of the calibration report. If any data "correction" (quotation marks used because this is a very delicate subject) is applied, the justification must rest on calibration reports on either side of the data period and the data in between. This report requires distribution to the project leader and the QC inspector, or at least a sign-off routing. If corrective action is initiated but not completed, a report of completion is required and has the same routing.

4.1.9.3 Audit Reports

Audit reports should confirm the calibration reports. If they do not, the assumption is that the audit report is correct. Whenever a measurement discrepancy exists, the cause of the difference must be found and resolved. If the audit measurements are wrong, the auditor will be smarter next time and all parties will have more confidence in the calibration reports. It is the responsibility of the auditor to include a report of the discrepancy between calibration data and audit data along with the explanation and solution of the discrepancy in the audit report. It is the responsibility of the operator to be sure that it is in the report. The documentation must be suitable for use in a court of law.

4.1.9.4 Reports to Management

Reports to management are of value to maintain the close communication necessary between the source of authority, top management, and the exerciser delegated authority, the QA organization. Whatever the structure of the organization, directed effort must be paid for and planned for through budgeting. Top management must know how the quality program is performing its intended, money saving role. There are about as many types of meteorological monitoring programs as there are applications. One fairly standard one is the 2-level, 60 m tower used at most nuclear power plants. Crutcher (1984) provides an insight into costs of a minimum system and an acknowledgement of the annual costs involved in operations and quality assurance.

"Costs are controlled by the design and reliability of the system, as well as the marketplace. Costs given here are approximate 1977 prices for presently available equipment sufficient to meet the minimum requirements of the Nuclear Regulatory Commission's Regulatory Guide 1.23 (formerly the USAEC Safety Guide 23). For the first two years these costs approximate one-third of a million dollars. These minimum costs do not include either office or storage space.

One tower, installation and equipment	$100,000
Annual maintenance cost	25,000
Annual cost of surveillance and quality assurance (including personnel and supplies, magnetic tape, paper etc.)	50,000
Annual cost of data listings, etc. based on 15-min. integrating intervals and automatic logging in digital form on magnetic tape, 13 parameters (channels) to a page, daily summaries	60,000

The cost of a mobile tower and equipment installation is essentially 50% of the cost of a permanent-type tower installation. Other costs remain essentially the same."

Of particular interest in this reasonably accurate estimate (ten years ago) is the ratio of annual costs to one-time costs, 1.35:1. Of course, the requirement of RG 1.23 is for valid data with documentation and quality assurance. Smaller systems cost less, but the often neglected provision for annual operating and QA costs are still necessary if valid data are required.

4.1.9.5 Discrepancy Reports

Some systems report discrepancies as a section of another report and some use a discrepancy report as a stand-alone vehicle to initiate corrections and report completed corrections. If it is a stand-alone report, some system of control is necessary to keep track of open reports and monitor progress toward completion (called follow-up or needling).

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Section 4.2
QA FOR WIND SPEED, WIND DIRECTION AND TURBULENCE
OUTLINE

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QUALITY ASSURANCE FOR WIND SPEED, WIND DIRECTION AND TURBULENCE

SUMMARY

This section discusses all aspects of the task of monitoring the wind at a particular site with an emphasis on quality assurance. A background chapter describes the nature of wind and the kinds of instruments commonly used to monitor its speed and direction. This section describes in detail the important aspects of the operation of conventional anemometers and wind vanes. Some discussion of secondary effect sensors is provided but the handbook is not intended to cover these instruments. The background information and the detailed information found in the following chapters are necessary for two kinds of tasks. One is to execute the responsiblity for the collection of valid data. The other is to audit or judge how well the first task was performed within the goals or regulations which caused the measurements to be made in the first place.

Specifications is the longest and in some ways the most detailed section. The premise is that an understanding in depth of the way the common sensors work is necessary before purchasing, installing and operating the instruments. Specifications set the performance parameters for the instrument or system. Careful definitions are given along with test methods which will equip the user to verify or to judge the work of others who verify conformance to specification.

Once the specifications are clearly understood, the process of purchasing and acceptance testing can be considered. The contention is that quality assurance is a vital aspect of defining that which is to be purchased and verifying the performance of the delivered system. When the valid system is in hand, the installation can be planned and implemented. The important process of orientation of the wind vane to TRUE NORTH is described in detail.

Calibration is a foundation on which claims of data validity are built. This important function may be practiced in a number of phases of the monitoring program. This chapter stresses documentation of the calibration findings and methodology. The use of the most inclusive methods practical in field conditions is advocated. Once the calibrated system has been installed, the routine performance of operational checks, preventive and corrective maintenance and quality control operations begin. The documentation of these operations provide the framework, resting on the foundation of calibration, to support the claim of data validity.

Performance audits add confidence to the documentation that the system is in control. Performance audit methods must be the most comprehensive methods possible for field challenges. This chapter describes some recommended audit methods and audit forms to support the methods. The performance audits and calibrations provide the data for the estimation of accuracy and precision described in the following chapter.

There is not room to include all the details or background information which might be needed or desired. A list of the references used for this section is found at the end of the section. If the reader needs additional information or is curious about peripheral subjects, the references will provide the answers or a start in search of the answer.

4.2.1 TYPES OF INSTRUMENTS

There are many ways to detect wind as it passes a point on Earth. Only those ways which reference a fixed point (or volume) will be considered in this handbook. This class of measurements is expressed in Eulerian coordinates where properties of the air are assigned to points in space at each given time (Huschke, 1970). The other class of measurement is expressed in Lagrangian coordinates. It is good to keep in mind that Eulerian measurements are frequently used in Lagrangian models. Or, in other words, monitoring data measuring wind on a tower are used to estimate where parcels of air move and how the concentrations of constituents of the parcel change in the process.

It is necessary to understand just how the measurement is made to adequately do the following:

- write procurement specifications,
- adopt and apply acceptance testing methods,
- site the sensors in the representative flow of interest,
- perform calibration and maintenance services,
- establish an effective quality control (QC) operation, and to
- evaluate audits used to estimate precision and accuracy of the data.

This section will describe how various kinds of instruments work. The thoroughness of the description in this handbook will be proportional to the frequency of use of the instrument in air quality applications.

Another background point deals with the nature of wind. There can be no question about the wind requiring a vector to describe fully a single measurement. The vector has direction in spherical coordinates (azimuth with respect to TRUE NORTH and elevation with respect to a horizontal plane) and length (speed) along that direction. It is common for many air quality applications to deal only with the presumably horizontal flow as measured by vanes and anemometers. In this case, the horizontal components of the vector are expressed as an azimuth angle from which the wind is blowing and the speed at which the air is passing the point of measurement. While each sample of wind requires both speed and direction, it is common to measure them separately. A series of samples may be summarized in different ways depending upon the application. The arithmetic mean of the samples is recommended for many applications (EPA, 1987b). The standard deviation of the samples is used to describe the level of turbulence in the air.

4.2.1.1 Common Mechanical Sensors

4.2.1.1.1 Wind speed sensors

Common anemometers are either cup assemblies turning on a vertical axis or propellers turning on a vane-oriented horizontal axis. The cup anemometer is an empirical sensor in that the relationship between the rate of rotation and the wind speed is determined by testing rather than defined by theory. It is a linear relationship, for all practical purposes, above its threshold non-linearity and through the range of important application. It is an aerodynamic shape which converts the wind pressure force to torque (hence rotation) because of asymmetrical lift and drag. Its dynamic performance characteristics (starting threshold and distance constant) are density dependent but its transfer function (rate of rotation vs. wind speed) is independent of density. The cup is not very efficient and creates turbulence as the air flows through and around it. The linear speed of the center of a cup is only a half to a third the linear speed of the air turning it (Mason and Moses, 1984). The cup anemometer is omnidirectional to horizontal flow but exhibits a complicated reaction to vertical components. It may indicate speed slightly greater than the total speed when the flow is non-horizontal (MacCready, 1966).

The propeller anemometer is a more efficient shape. The helicoid propeller is so efficient that its transfer function can be specified from theory (Gill, 1973). It creates little turbulence as the air flows mostly through it, turning like a nut on invisible threads. The propeller measures wind speed when it is oriented into the wind by a vane. Its errors from imperfect alignment with some mean vector are small, being nearly proportional to the cosine of the angle of misalignment.

In either of these types of anemometers, the rate of rotation is sensed by some transducer. Tachometer generators, a.c. frequency generators, light choppers and shaft revolution counters have all been used. It is important to know how the transducer works if the performance of the anemometer is to be challenged for a QA purpose.

4.2.1.1.2 Wind direction sensors

The wind vane is perhaps the simplest of instruments. A fin is tied to a vertical shaft such that when force is applied to the area by the wind, it will turn the shaft seeking a minimum force position. The relationship of the shape, size and distance from the axis of rotation of the fin to the bearing assembly and transducer torque requirements determines the starting threshold. These attributes of the fin area along with its counterweight determine the dynamic performance characteristics of overshoot (damping ratio) and delay distance (distance constant) of the direction vane. While its equilibrium position is insensitive to density, the dynamic response characteristics and threshold are density dependent.

Vane design is of little importance if the average wind direction is all that is required. If turbulence parameters are of interest, as they usually are or should be, the design of the vane becomes important. The vane transducer is usually a potentiometer, but synchros, shaft encoders, capacitors and Hall effect devices have been used. It is fairly common to find the range of the sensor to be "540 degrees" rather than the physically true 360°. The reason is related to the problem of a continuous range (a circle) with a discontinuous output (0 to n volts). It is important to know how the transducer works if the performance of the wind vane is to be challenged for a QA purpose.

A special direction vane is the bivane which has the vertical range of ± 45° to 60° in addition to the full azimuth circle. The additional range brings with it the need to neutralize gravity by having a perfectly balanced vane assembly. Bivanes can be conditionally out of balance, such as happens when dew forms and then evaporates from the tail fins. The effect of this imbalance on threshold and performance is complicated. Horizontal vanes can be designed to be stable in the horizontal even when slightly out of balance. The effect of this design is to add the vane horizontal restoring force to the wind force, again a complication.

4.2.1.1.3 Fixed component sensors

Propeller anemometers exhibit something like a cosine response to a wind along some line other than the axis of the propeller. The degree with which this response represents a cosine is a function of the design of the propeller. If the cosine response is perfect, the fixed propeller accurately reports the component of the wind parallel to the axis of the propeller. If three propellers were located on fixed X, Y and Z axes, the three outputs would define the components of a three dimensional wind vector. From a QA perspective, the accuracy of the wind speed and direction data are related to the determination of the component errors and the algorithms used to correct for them. Often ill-defined are the errors from the interference of one propeller on another and the errors when the beyond-threshold-nonlinearity speed has not been reached. It is the speed of the component parallel to the anemometer axis that the propeller responds to, not the total speed. A 5 m/s wind with a 5° up angle and 5° off the Y axis will provide a 0.44 m/s wind for the W and X propellers. A 50% error in the X propeller because of threshold nonlinearity would cause an insignificant 0.014 m/s error in the wind speed and a 2.5° error in wind direction. A 50% error in the W propeller for the same reason would cause a 50% error in the W component (0.22 m/s reported rather than the true 0.44 m/s).

4.2.1.2 Secondary Effect Sensors

4.2.1.2.1 In-situ sensors

Several meteorological instrument books contain information on a variety of wind instruments. See Mason and Moses (1985) and Middleton (1953) for greater depth and variety.

The three component sonic anemometer is considered in some circles as the standard for wind measurement. For those applications where the contribution of small eddys is important, it is an excellent choice. As with many of the secondary effect sensors, it is a research tool requiring considerable attention from the operator. It is not a good choice for routine monitoring. It has its own set of error sources when it is used for measuring long-term (tens of minutes) averages and standard deviations. Single component sonic anemometers deployed as W sensors may become the standard for this difficult measurement. The secondary effect for this instrument is the transport of sound waves in the air.

The hot wire or hot film anemometer is also a research tool which measures the wind speed component perpendicular to a heated cylinder. The secondary effect for this instrument is the removal of heat by the air measured by the current it takes to replace the heat. There are some new designs of this type of instrument which are intended to be monitoring instruments.

4.2.1.2.2 Remote sensing devices

There are two Doppler shift instruments which measure wind remotely by analyzing the return from transmitted energy pulses. The most important for the boundary layer applications is the acoustic Doppler (SODAR) sounder. It depends on the back scatter from small temperature differences that tag the air for motion measurement. The other Doppler uses electromagnetic energy to measure winds through the troposphere. There are also some Doppler applications using lasers as the energy source. These systems are complicated. A QA effort related to systems of this type will require special study of the system and ingenuity to find other ways of measuring what they are measuring. In the case of the SODAR which is being used in monitoring applications for air quality programs, a reasonableness test with another instrument capable of measuring winds aloft is more likely to produce useful information than is a challenge designed to report the accuracy of the SODAR.

4.2.2 SPECIFICATIONS

The purpose of defining specifications is to give unambiguous meaning to the terms used by all those who are concerned that the instruments and systems selected and operated will meet the needs of the application or project. This starts with procurement specifications and ends with supporting claims of data quality. These specifications provide the basis for receiving inspection and testing. The wind is the most important variable to be measured and its specifications are the most complicated. Specifications discussed here will also include some aspects of the measurement system.

Project and application requirements vary. To make this handbook as specific as possible, the examples used will be consistent with those presented in the On-Site Meteorological Program Guidance for Regulatory Modeling Applications (EPA, 1987b). The specifications will be discussed in order of their importance and then summarized at the end of the sub-section.

4.2.2.1 Wind Speed

4.2.2.1.1 Threshold

4.2.2.1.1.1 Threshold definition

One of the keys to a good wind sensor is a low threshold. The threshold is also the one performance characteristic which will certainly change with time because of bearing degradation. There is no standard definition of threshold so different manufactur-ers may apply different tests to establish their threshold specifica-tion. Absence of a standard or definition of the specification makes it difficult to specify a meaningful value. The following definition comes from Standard Test Method for DETERMINING THE PERFORMANCE OF A CUP ANEMOMETER OR PROPELLER ANEMOMETER (Draft 6) (ASTM, 1985):

> "Starting threshold ($U_{\,}$,m/s)--the lowest wind speed at which a rotating anemometer starts and continues to turn and produce a measurable signal when mounted in its normal position."

A starting threshold specification, 0.5 m/s for example, should include a footnote describing the meaning of the specification. In the example above, it might say: 0.5 m/s (1)

> (1) "as determined by wind tunnel tests conducted on production samples in accordance with ASTM D22.11 test methods."

All rotating anemometers are non-linear as they go from not turning to turning at a rate predicted by their linear transfer function. Note that the definition does not require linear output at threshold, only continuing turning and measurable signal. If the manufacturer provides an accuracy specification which is independent of speed, the presumption is that the accuracy specification is met at threshold. Consider a hypothetical cup with a transfer function, i.e., the relationship between rate of rotation and wind speed, as follows:

$$U = 0.2 + 1.5\,R$$

where U is wind speed (m/s) and
R is rate of rotation (rps)

The transfer function would have been found by using a least squares fit (linear regression) to wind tunnel data. The ASTM method uses the wind speeds well above the starting threshold to avoid bias from the non-linear threshold. In Figure 4.2.2.1 the lowest 2 m/s of the hypothetical performance curve is shown along with the contribution of the offset to the system output. The variable part of the transfer function (U = 1.5 R) coming from the cup rotation is shown theoretically as the straight line from 0.2 m/s to an output of 1.8 m/s when the wind speed is 2 m/s. The triangles show the actual output from the cup rotation. They start to turn at 0.3 m/s (threshold) and reach the theoretical line at about 0.8 m/s. The parallel line through the origin simply adds the constant offset to the cup rotation output. The measurement error is the difference between the diamonds in the figure and the ideal straight line. It starts at +0.2 m/s, goes to -0.1 m/s at 0.3 m/s, and then gets smaller as the nonlinearity of the threshold decreases.

The offset is defined either by the linear regression or by the arbitrary choice of the manufacturer. If it is the former, the starting threshold will always be larger than the offset. If it is the latter, the starting threshold may be either side of the offset. The manufacturers of the common small three cup anemometer often set an offset voltage in their signal conditioner as shown in Figure 4.2.2.1. For this hypothetical cup, the offset voltage is critical to its meeting the accuracy specification discussed in 4.2.2.1.2. Sensitive propeller anemometers have a much smaller offset because they develop more force (torque) per m/s. Some offsets are so small that there is no advantage or need to use an offset voltage. See Baynton (1976) and Lockhart (1977) for further discussion of the errors of rotational anemometers, particularly at the threshold.

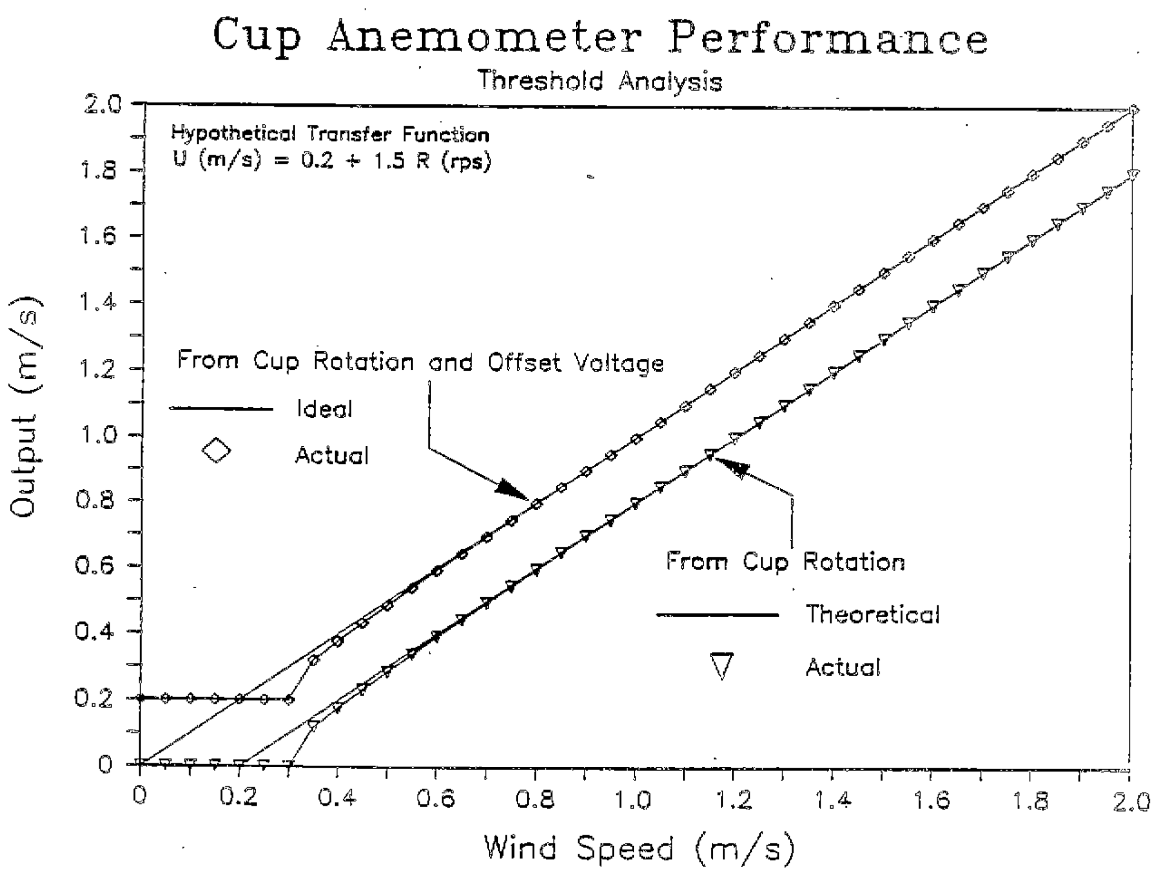


Figure 4.2.2.1 *A hypothetical cup anemometer threshold analysis.*

4.2.2.1.1.2 Threshold Measurement

There is only one way to measure starting threshold. It requires a wind tunnel capable of accurate operation below 1 m/s. One standard methodology is defined in ASTM (1985) and described in Lockhart (1987). However, it is possible to estimate the starting threshold by matching the torque which is required to keep a cup or propeller from turning at a known wind speed (in a wind tunnel) with the starting torque of the anemometer bearing assembly. Lockhart (1978) provided the torque relationship as a function of wind speed for four anemometer shapes.

Table 4.2.2.1 contains values calculated with these data by using the relationship

$$T = K u^2$$

where T is torque ($g\ cm^2/sec^2$)
u^2 is the square of the wind speed (m/s)
K is a constant for the aerodynamic shape (g)

The values in the table were calculated from this formula using the K values from Lockhart (1978).

Table 4.2.2.1 - Torque Developed vs. Wind Speed

Speed (m/s)	cup #1 (g-cm)	cup #2 (g-cm)	prop #3 (g-cm)	cup #4 (g-cm)
0.1	0.014	0.027	0.049	0.148
0.2	0.056	0.108	0.196	0.592
0.3	0.126	0.243	0.441	1.332
0.4	0.224	0.432	0.784	2.368
0.5	0.350	0.675	1.225	3.700
1.0	1.4	2.7	4.9	14.8

#1 Teledyne Geotech 170-42 (20.3 g) K= 1.4
#2 MRI Model 1022 (48.3 g) K= 2.7
#3 R.M. Young Model 21180 (9.7 g) K= 4.9
#4 MRI Model 1074 (186.8 g) K=14.8

The torques listed are those acting on the sensor when the sensor is restrained in a wind field at the speed listed. If the sensor bearing assembly has a starting torque less than the torque provided at that speed, and the restraint is removed, it will start turning. The torque watch used for the low speed end of the wind tunnel tests was a Waters Model 366-3 with a range from 0.003 oz-in (0.216 g-cm) to 0.03 oz-in (2.16 g-cm). To convert oz-in to g-cm, multiply by 72.

The method of using a starting torque measurement to find the sensor starting threshold will become standard only with the publishing of K constants by the manufacturers. One manufacturer (R.M. Young Co.) provides the K value for anemometers. These values are shown in Table 4.2.2.2.

Table 4.2.2.2 - Anemometer K Values

Type	Model	K
Polypropylene Cupwheel	No. 12170C-100cm	1.4
Polypropylene Propeller	No. 08234-18x30cm	2.5
Polystyrene Propeller	No. 21282-19x30cm	3.6
Polystyrene Propeller	No. 21281-23x50cm	5.0

4.2.2.1.1.3 Starting Torque Measurement

The starting torque of an anemometer bearing assembly will increase in time because of wear and dirt. The starting torque, with the cup assembly or propeller removed, can be measured. Starting torque measurement is simple in concept but sometimes difficult in application. An experienced meteorological instrument technician can tell if a bearing assembly is in need of service by simply feeling the shaft or rotating or spinning the shaft and listening to its sound. The trouble with this practice is that it is not quantitative. It works for field servicing instruments but does not provide documentation suitable for a quality control program. Another qualitative practice is to roll the sensor slowly over a smooth horizontal surface watching the shaft not turn as the sensor turns around it (see Figure 4.2.2.2). Set screws and other asymmetries apply a torque which keeps the shaft from turning while the sensor moves around it. If the applied torque could be measured, this method would be quantitative.

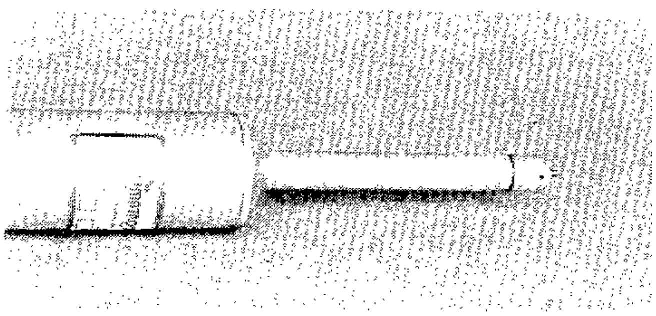


Figure 4.2.2.2 *Climatronics F460 torque test for speed sensor*

The measurement of the starting torque of the bearing assembly provides only an approximation of the starting threshold of the anemometer, particularly cup anemometers. The absence of the cup weight may lower the starting threshold of the cup bearing assembly but there is no evidence that this is an important consideration. At this point in time there is no better way to estimate and document in the field and in units of wind speed this important specification, the starting threshold of the anemometer.

The direct measurement of starting torque requires some device which can apply a known torque. The most common, perhaps, is the Waters Torque Watch. A model 366-3 is shown in Figure 4.2.2.3 applied to a Climatronics cup anemometer sensor. The measurement requires some degree of care and skill. The torque watch has a square shaft which fits into a square hole in the connecting fixture. The torque watch is turned while holding its shaft in line with the anemometer shaft, without end loads. The indicator is watched and when the shaft turns the maximum reading is recorded. This process needs to include at least one full turn of the anemometer to be sure the maximum friction in the bearing assembly is encountered. The torque watch measures either clockwise or counterclockwise. Use only the rotation sense required by the cup assembly or propeller. The range of the torque watch may not be as sensitive as one would like. If the model 366-3 is used on anemometer #1 in Table 4.2.2.1, the threshold (0.003 oz-in or 0.216 g-cm) will not measure equivalent speeds below 0.4 m/s. If the torque watch turns the shaft without reaching the lowest scale point, all that can be said is that the starting threshold of the anemometer is less than 0.4 m/s.

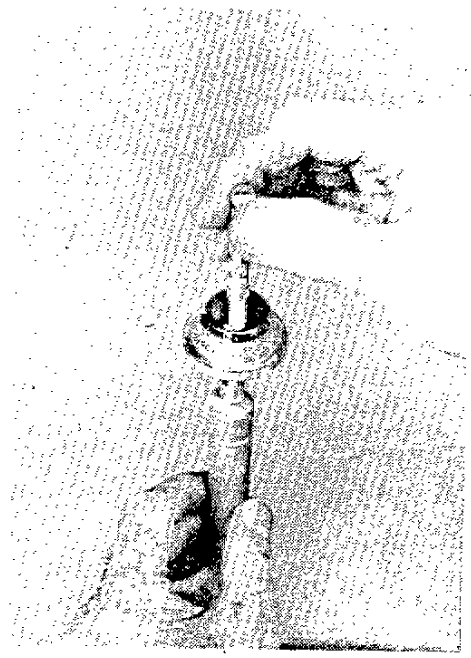


Figure 4.2.2.3 *Waters Torque Watch*

Another torque watch is the GM-CM Torqmeter 781 with a 0.1 to 2.1 g-cm range (0.001-0.029 oz-in), shown in Figure 4.2.2.4 mounted to a Teledyne Geotech 1565C wind direction sensor. A third torque measuring device is the simple Torque Disc, model 18310 made by R.M. Young Co., shown in Figure 4.2.2.5. This is a fundamental device which does not need expensive calibration. Weights (screws) are attached at distances from the center of rotation. The force of gravity provides g-cm torques at the center of rotation of the intentionally out of balance disc. The shaft being tested must be horizontal and symmetrical in mass. A cup anemometer shaft which does not turn while the sensor is slowly rolled along a flat surface will not work with the Torque Disc. The g-cm torque applied equals the weights and distances when the weights are in the same horizontal plane as the shaft. Calibration results from weighing the weights and measuring the distances. An appropriate interface fixture would allow the Torque Disc to be used to calibrate a torque watch.

Figure 4.2.2.4 *Gm-Cm*

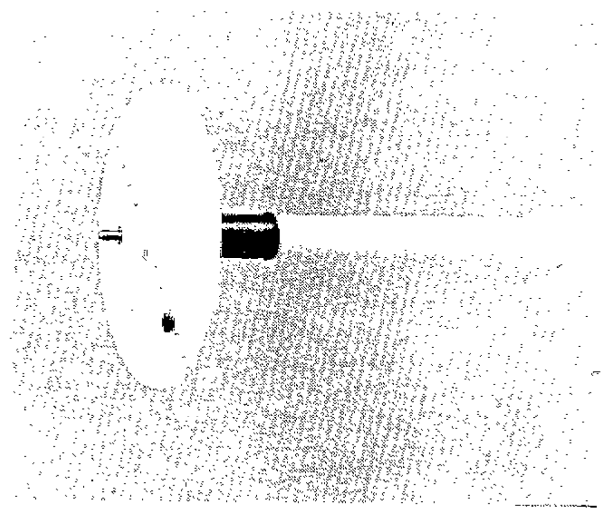
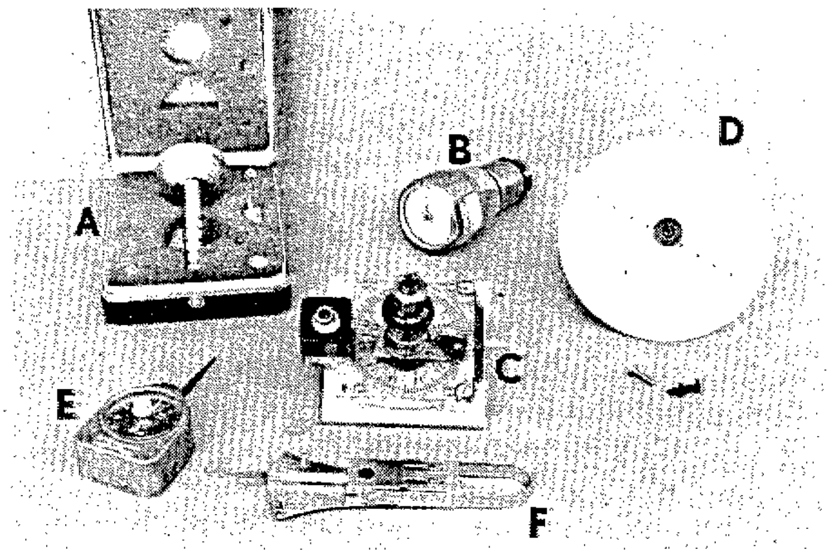


Figure 4.2.2.5 *Young Torque Disc*

There are several ways to measure torque but the available instrumentation to make the measurement is limited. Figure 4.2.2.6 is a collection of spring-type torque watches, spring scales and circular discs capable making torque measurements within narrow ranges and specific orientations. It is necessary to become familiar with these devices and how they are correctly used.



A - Waters Torque Watch Model 366-3 (0.2-2.0 g-cm)
B - Waters Torque Watch Model 651X-3 (18-360 g-cm)
C - GM-CM Torqmeter Model 781 (0.1-2.1 g-cm)
D - Young Torque Disc Model 18310 (0.1-15 g-cm)
E - Haldex AB Gram Gauge (1-10 g)
F - Young Gram Gauge Model 18330 (0-10 g)

Figure 4.2.2.6 *Various Torque Measuring Devices*

4.2.2.1.2 Accuracy

4.2.2.1.2.1 Definition

The classic definition of accuracy is the comparison of a measured value to a true value expressed as a bias term plus or minus a random uncertainty (precision). The bias term may be conditional with respect to the best fit straight line; it may vary with wind speed or angle of attack.

When accuracy is specified, the kind of true value to be used to test the accuracy claim must also be specified. Usually the buyer expects the "true value" to be the wind speed where the anemometer is sited. The manufacturer expects the "true value" to be the near laminar flow of a calibration wind tunnel. Some auditors expect the "true value" to be the output predicted by the transfer function when the anemometer is rotated at a known rate. Let us label the kind of accuracy as follows:

- A(1) - accuracy with respect to the horizontal component of wind speed at the sited location,
  - A(1a) - instrument response
  - A(1b) - siting representativeness
- A(2) - accuracy determined in a wind tunnel, and
- A(3) - accuracy of conversion of rate of rotation to output.

A(3) is the easiest to measure and represents most of the claims for data accuracy from audit reports. It requires, usually, a measure of the offset voltage (or equivalent m/s) and the combination of offset and output from the rate of rotation to output converter.

A(2) requires a calibrated wind tunnel and it is a more difficult and more expensive accuracy to determine. It does provide a check on the manufacturer's generic transfer function plus the variation in production individuals represented by the individual being tested. The wind tunnel calibration test provides a specific transfer function which can be used to change the signal conditioning to get the smallest error of an A(2) type for that specific system. Serial numbers should be recorded with the test results.

Some manufacturers do not identify their cup assemblies or propellers with numbers. Assume an A(2) accuracy is found in a wind tunnel test and compared to the generic transfer function used for A(3) operations. Assume the test shows that the A(3) value is uniformly 10% low. Assume the operators took a year of data with A(3) accuracy tests showing insignificant errors. The error to the A(2) level is a 10% bias and the data can be corrected for the year. This action requires either evidence or good reason to believe that there was no physical change to the cup assembly over the year and that the individual tested was the one used during the year.

There are still unknowns of the A(1) type to consider. These are usually conditional biases and often impossible to define. They may be recognized and their impact estimated. There are two types of these errors. One is the consequence of the anemometer design in the flow field it is to measure., A(1a). The other is a result of assumptions of representativeness, A(1b).

The discussion of A(1a) errors requires an understanding of conventions for the use of u, v and w. In traditional diffusion applications, the statistics for wind representing a period of time refer to u as the speed of the horizontal component along the direction of the mean wind, v as the speed of the horizontal wind component perpendicular to the mean direction, and w as the speed of the vertical wind component. Another convention applies to fixed component anemometers such as the UVW propeller array. Here, the U is the east-west component of the wind in a Cartesian coordinate system (a west wind is positive); V is the north-south component of the wind (a south wind is positive); and W is the vertical component of the wind (upward moving wind is positive)(Stull, 1988).

MacCready (1966) characterized errors in anemometers when operating in a turbulent flow. A cup anemometer has a u-error because of a different response "constant" to an increasing speed than to a decreasing speed, so-called overspeeding. With modern sensors, this is usually a small error of a percent or two, depending on sensor design and height above ground. A cup anemometer has no v-error since it is insensitive to changes in direction, but it does have a w-error caused by non-horizontal flow. This error can easily be 10% and larger with some designs (Lockhart, 1987). A vane oriented propeller will have small v-errors and w-errors from misalignment. These will be small because the propellers respond nearly as the cosine of the misalignment angle, 2% for a 10 degree misalignment. The u-error is too small to measure for light weight helicoid propellers. These are all A(1a) errors and they vary as the wind varies.

A(1b) errors deal with the assumption is that the anemometer is measuring what the true wind would be at the point of measurement if the anemometer were not there. This is a question of representativeness and not instrumentation but it can have a large impact on the question of data accuracy. The influence of any supporting structure can bias the flow which the anemometer faithfully measures. If the assumption goes further to equate the measurement to its physical height above ground, and if the anemometer is mounted on a 2 m pole on top of a large 8 m building, the bias with respect to a 10 m flow over a flat field will be the fault of the building. These errors are of the A(1b) type. If the pole is on the edge of the building, the distortion of the building will provide non-atmospheric errors of the A(1a) type to be combined with the A(1b) type. These types of errors are very difficult to define and virtually impossible to correct. Data from an anemometer mounted in a questionable site, after the A(2) and A(3) errors have been calibrated out, could be compared with data from a vane oriented propeller anemometer mounted in a space where the subject anemometer is assumed to represent. The difference in these collocated measurements may be used to estimate the magnitude of A(1) errors. The A(2), A(3) and A(1a) errors are the ones to concentrate on minimizing. See 4.2.4.1 for siting guidance.

4.2.2.1.2.2 Measurement of accuracy

The accuracy of an anemometer is found by comparing its output to the known speed in a wind tunnel. A calibrated wind tunnel has uncertainties associated with its operation. These include instrumentation errors in measuring the wind speed in the tunnel when it is empty (0.1 mph or 0.05 m/s in the NBS wind tunnel above 2 mph) and the inhomogeneity of wind speed in the test section away from the boundary layer (a function of the tunnel design). The turbulence level in the wind tunnel test section should be homogeneous across the test section with most of the energy in eddy sizes which are small compared to the size of the anemometer. When this is true, and it usually is, turbulence does not influence the calibration. Fluctuations in the tunnel speed can be thought of as long wave length longitudinal turbulence. This "turbulence" can influence the calibration without careful measurement synchronization and time averaging.

When an anemometer is placed in the test section for calibration, consideration must be given to blockage errors, which are dependent on the ratio of the size of the instrument to the size of the test section. Also interference errors, which are dependent on the placement of the anemometer with respect to the wind tunnel instrumentation need to be considered. Small calibration wind tunnels may themselves be calibrated with an anemometer which has been run in the NBS wind tunnel. It is also a common practice to run two anemometers side by side, one of which has an NBS calibration curve. It is prudent to reverse the positions from time to time to verify test section homogeneity. It is not reasonable to expect such calibrations, even though they are "traceable to NBS" by some definition, to have an accuracy better than 0.2 mph (0.1 m/s).

While a calibrated wind tunnel is the recognized standard method for calibrating an anemometer, a fundamental (but not very practical) calibration is possible by moving an anemometer over a measured length in a measured period of time through still air (Lockhart, 1985b and Stearns, 1985). Most manufacturers have samples of their products calibrated by NBS to establish for their design a generic relationship between wind speed and rate of rotation, measured by counting pulses, frequencies or output voltages. This relationship is then used as the transfer function to define what the signal conditioning electronics or other output devices require to express the measured rate of rotation in units of wind speed. Some manufacturers test and adjust each cup wheel or propeller to fit the generic relationship within some error band.

Baynton (1976) discusses the calibration of anemometers and shows the results of tests of 12 different kinds of anemometers in the National Center for Atmospheric Research (NCAR) wind tunnel. He compares his calibration to the manufacturer's calibration or generic relationship. Except for the Aerovane, which probably was too large for the NCAR tunnel, the difference was within ±3%. He also discusses the difference between an anemometer transfer function which goes through the origin, of the form

$$Y = bX,$$

and the transfer function with an offset or threshold, of the form

$$Y = a + bX.$$

Table 4.2.2.3 summarizes data from his Table 1 and Table 5.

Table 4.2.2.3 Wind Tunnel Test Results From Baynton

Type of Anemometer	a (m/s)	b (m/rev.)	E
Gill 4-blade helicoid propeller	0.073*	0.309	1.03
Gill 3-blade helicoid propeller	0.011*	0.487	1.03
Aerovane helicoid propeller	0.233	1.356	0.93
Taylor Biram's propeller	0.145	0.255	1.00
Casella Sensitive	0.467	1.404	0.98
Thornthwaite	0.331	1.476	0.97
INSTAAR †	0.316	1.597	
Climet 011-1	0.265	1.382	1.01
TechEcology ‡	0.275	1.391	
Gill 3-cup	0.250	1.057	
Electric Speed	0.610	2.728	1.03
Bendix Totallizer Model 349	0.588	2.605	0.97
MRI Model 1074 ††	0.087*	2.314	

* a is not significantly greater than zero
† Institute for Arctic and Alpine Research, Boulder, Colo.
‡ Analysis of NBS data provided by L. Petrall i
†† Data from Lockhart (1977)
E is the ratio of the test result to the mfg.'s calibration.

Baynton lists the value of "a" for the 12 anemometers he tested, which ranged from nearly zero (0.01 m/s) to 0.6 m/s. One purpose of his paper was to caution users of "wind run" instruments of the errors associated with ignoring "a." Wind run is generally used to describe those anemometers which count shaft rev-olutions over a long period of time or are geared to a counter or recorder in such a way that the output is in units of speed. These instruments cannot pro-vide an offset. Lockhart (1977) shows that some cup designs, specifically the Meteorology Research, Inc. Model 1074 used on the Mechanical Weather Station, can be nearly as accurately described without an offset (a=0) as with one (a=0.03). Table 4.2.2.4 lists the NBS data and the linear regressions to sup-port this fact. The residual errors from each model are plotted in Figure 4.2.2.7.

Table 4.2.2.4 NBS Test Data for MRI Model 1074

Test No.	------NBS------ Output Freq. (hz)	Tunnel Speed (mph)	Y Tunnel Speed (m/s)	X Output /132 (rps)	-------Linear Regression------- X' (m/s)	X'-Y (m/s)	X" (m/s)	X"-Y (m/s)
1	14	0.9	0.4	0.11	0.28	-0.12	0.25	-0.15
2	28	1.3	0.6	0.21	0.53	-0.05	0.50	-0.08
3	65	2.8	1.3	0.49	1.19	-0.07	1.15	-0.10
4	88	3.7	1.7	0.67	1.59	-0.06	1.56	-0.09
5	112	4.7	2.1	0.85	2.02	-0.08	1.99	-0.11
6	240	9.6	4.3	1.82	4.29	-0.00	4.26	-0.03
7	380	15.1	6.8	2.88	6.77	0.02	6.75	-0.00
8	500	19.9	8.9	3.79	8.90	0.01	8.88	-0.02
9	625	24.9	11.1	4.73	11.12	-0.01	11.10	-0.03
10	755	29.8	13.3	5.72	13.43	0.10	13.41	0.09
11	880	34.7	15.5	6.67	15.64	0.13	15.63	0.12
12	1005	39.6	17.7	7.61	17.86	0.16	17.85	0.15
13	1255	49.5	22.1	9.51	22.30	0.17	22.29	0.16
14	1500	59.3	26.5	11.36	26.64	0.13	26.64	0.13
15	1755	69.6	31.1	13.30	31.17	0.05	31.17	0.05
16	1995	79.6	35.6	15.11	35.42	-0.16	35.43	-0.15
17	2265	90.2	40.3	17.16	40.21	-0.11	40.23	-0.10
18	2530	100.7	45.0	19.17	44.91	-0.10	44.93	-0.08

Test date - 11/18/75 MRI, Altadena, Calif. Model 1074 @ 132/rev.

	X'
Regression Output:	No. 1-18
Constant	0.032089
Std Err of Y Est	0.106914
R Squared	0.999949
No. of Observations	18
Degrees of Freedom	16
X Coefficient(s)	2.341656
Std Err of Coef.	0.004174

	X"
Regression Output:	No. 1-18
Constant	0
Std Err of Y Est	0.106039
R Squared	0.999946
No. of Observations	18
Degrees of Freedom	17
X Coefficient(s)	2.344297
Std Err of Coef.	0.002764

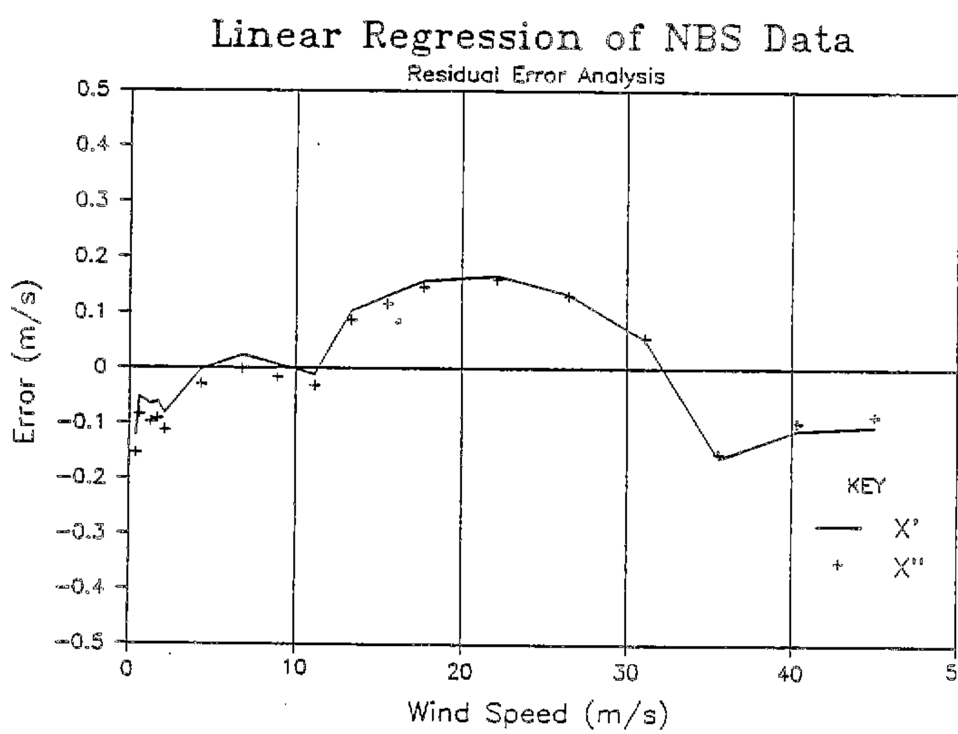


Figure 4.2.2.7 *Residual Errors from MRI Model 1074*

A similar analysis for a propeller anemometer is shown in Table 4.2.2.5. These data come from a test in the Atmospheric Environment Service (AES) of Canada wind tunnel on a propeller anemometer being used in a "round robin" experiment to estimate the accuracy of wind tunnel calibrations. Each test was run for 100 seconds. The tunnel speed is an average of one second samples taken every ten seconds by AES. The sensor count is a total for 100 seconds from the light chopper delivering 10 pulses per revolution. Each test was replicated and tests 3 and 4 were also replicated in tests 19 and 20. Two linear regressions were run. The first, and best fit, allowed the intercept of the X axis, or zero offset in ASTM language, to be calculated. The second forced the straight line through the origin. This latter method yields a constant slope or pitch (meters per revolution) which when multiplied by the rate of rotation (revolutions per second) results in wind speed (meters per second). The residualerror from these two regressions are plotted in Figure 4.2.2.8.

It is characteristic for helicoid propellers to show a better correlation with wind tunnel speeds than does a cup anemometer. This is because propellers generate torque uniformly without sensitivity of position. Three-cup assemblies, on the other hand, produce three peaks and three valleys in torque for each revolution (Lockhart, 1985). Either type of anemometer can be calibrated to an accuracy sufficient for most applications.

4.2.2.1.2.3 Application of accuracy specifications

An accuracy specification should include enough information to define the type of accuracy intended and the method by which accuracy claims may be tested. Here are a few examples of accuracy requirements.

In the Ambient Monitoring Guidelines for Prevention of Significant Deterioration (PSD) (EPA, 1987a), it states that for horizontal wind systems "Wind speed systems should be accurate above the starting threshold to within 0.25 m/s at speeds equal to or less than 5 m/s. At higher speeds, the error should not exceed 5 percent of the observed speed (maximum error not to exceed 2.5 m/s)." In the On-Site guide (EPA, 1987b) in 8.1.1 it states "Accuracy (error)(1)(2) ≤(0.2 m/s +5% of observed)

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

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

By implication, the latter specification refers to accuracy type A(2), although the expectation is that A(1) will be included by careful siting. This expectation must be addressed with experienced subjective judgment.

Assume a system is to be used in accordance with EPA (1987b), and an "off the shelf" anemometer is purchased. The manufacturer states that the sensor delivers 30 pulses per revolution (ppr) with a transfer function from revolutions per second, R (rps), to wind speed, U (m/s), of

$$U\ (m/s) = 0.224 + \frac{R \times 30}{21.275} = 0.244 + \frac{freq.}{21.275}$$

$$= 0.224\ (m/s) + 1.410\ (m/r)\ R\ (rps).$$

Table 4.2.2.5 NBS Test Data for Young 27106 at AES

	-------AES------		Y	X	-------Linear Regression-------			
Test No.	Output Count (*)	Tunnel Speed (m/s)	Tunnel Speed (m/s)	Output /1000 (rps)	X' (m/s)	X'-Y (m/s)	X" (m/s)	X"-Y (m/s)
1	3660	1.14	1.14	3.66	1.15	0.01	1.09	-0.05
2	3675	1.14	1.14	3.68	1.15	0.01	1.09	-0.05
3	10889	3.27	3.27	10.89	3.28	0.01	3.23	-0.04
4	10911	3.27	3.27	10.91	3.29	0.02	3.24	-0.03
5	18108	5.42	5.42	18.11	5.41	-0.01	5.37	-0.05
6	18207	5.42	5.42	18.21	5.44	0.02	5.40	-0.02
7	25418	7.59	7.59	25.42	7.57	-0.02	7.54	-0.05
8	25433	7.61	7.61	25.43	7.58	-0.03	7.55	-0.06
9	33006	9.82	9.82	33.01	9.81	-0.01	9.80	-0.02
10	33003	9.83	9.83	33.00	9.81	-0.02	9.80	-0.03
11	40163	11.96	11.96	40.16	11.92	-0.04	11.92	-0.04
12	40139	11.95	11.95	40.14	11.92	-0.03	11.91	-0.04
13	47636	14.13	14.13	47.64	14.13	0.00	14.14	0.01
14	47577	14.14	14.14	47.58	14.11	-0.03	14.12	-0.02
15	55102	16.35	16.35	55.10	16.33	-0.02	16.35	0.00
16	55105	16.30	16.30	55.11	16.34	0.04	16.36	0.06
17	62613	18.53	18.53	62.61	18.55	0.02	18.58	0.05
18	62795	18.56	18.56	62.79	18.60	0.04	18.63	0.07
19	10930	3.29	3.29	10.93	3.29	0.00	3.24	-0.05
20	10931	3.28	3.28	10.93	3.29	0.01	3.24	-0.04

	X'
Regression Output:	No. 1-20
Constant	0.067574
Std Err of Y Est	0.023965
R Squared	0.999954
No. of Observations	20.00
Degrees of Freedom	18.00
X Coefficient(s)	0.295224
Std Err of Coef.	0.000279

	X"
Regression Output:	No. 1-20
Constant	0.000000
Std Err of Y Est	0.043528
R Squared	0.999944
No. of Observations	20.00
Degrees of Freedom	19.00
X Coefficient(s)	0.296803
Std Err of Coef.	0.000258

(*) 10 pulses per revolution counted for 100 seconds.

Atmospheric Environment Service of Canada April 12, 1983 with J. Earle Chapman, Young 27106 @ 10/rev.

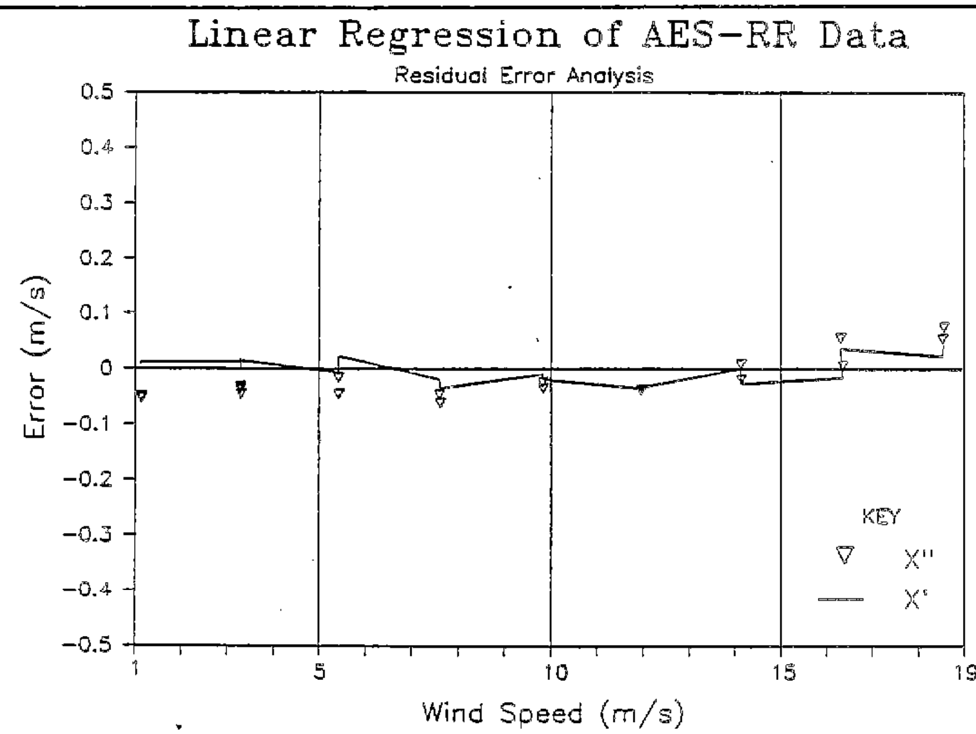


Figure 4.2.2.8 *Residual Errors from Helicoid Propeller*

Assume that an NBS test was conducted after a year of operation and the results provided a least squares analysis of

U (m/s) = 0.301 (m/s) + 1.387 (m/r) R (rps).

What action is suggested by this finding? Throughout the year the operator had the electronics trimmed to output 0.224 m/s when the cups were not turning and 14.325 m/s when the cups were turning at 10 rps. The A(3) error in converting R to U is 0.00. The A(2) error can be expressed as follows:

Generic transfer function: U = 0.224 + 1.410 R
Wind tunnel (truth): U' = 0.301 + 1.387 R
The error (E, m/s) is U - U' or E = -0.077 + 0.023 R
In terms of the measured speed, U, E = -0.081 + 0.0163 U

Table 4.2.2.6 compares this error with the specification at different rates of rotation. The 1.6 percent overestimation of speed by the generic transfer function is not large enough to bother with data correction. The data meet the accuracy guidelines with two thirds of the allowable error unused. At the next calibration the system should be adjusted to the wind tunnel derived transfer function.

Table 4.2.2.6 Wind Speed Errors

R (rps)	U (m/s)	U' (m/s)	E (m/s)	Allowed (m/s)	Used (%)
0.000	0.224	0.301	-0.077	±0.20	38
1.225	1.951	2.000	-0.049	±0.30	16
3.388	5.001	5.000	0.001	±0.37	0
6.993	10.084	10.000	0.084	±0.45	19
14.203	20.250	20.001	0.249	±0.81	31

4.2.2.1.2.4 Precision

The definition of accuracy describes a bias term and a variable term akin to precision. Traditionally, precision describes the uncertainty with which a measuring process or instrument realizes the measured value when that being measured is the same thing and is repeatedly measured. The key to finding the variability of a measuring process is to use a non-varying subject. In meteorology, and particularly in anemometry, it is not possible to have, with certainty, a non-varying subject. The ASTM subcommittee D-22.11 dealt with this problem by writing the Standard Practice for DETERMINING THE OPERATIONAL COMPARABILITY OF METEOROLOGICAL MEASUREMENTS - D4430-84 (ASTM, 1984). This work was patterned after Hoehne (1973) in which he defines Functional Precision as the root-mean-square of a progression of samples of the difference between simultaneous measurements made by identical instruments collocated in the atmosphere. Operational comparability applies to two different kinds of instruments rather than identical ones. This method recognizes that, from an operational perspective, the precision of a measurement can be estimated by know-ing how well identical or similar instruments measure the "same" flow.

An EPA project collected data in Boulder, Colorado in 1982 to add to the literature some estimates of comparability. Finkelstein et al. (1986) published in the refereed literature the material published by NOAA in Kaimal et al. (1984). Lockhart (1988) re-analyzed these data and concluded that the operational precision of anemometers at 10 m is no larger than 0.2 m/s. Operational precision is the standard deviation of a series of difference measurements which is equivalent to the operational comparability with all the bias (mostly calibration error) removed.

An expression of accuracy for an anemometer operating on a 10 m tower in the atmosphere can be expressed as some function of speed [f(u)], which comes from the wind tunnel test, A(2), plus or minus 0.2 m/s. This estimate does include the influence of turbulence on the sensor since the 0.2 m/s comes from collocated cups and vane oriented propellers operating in a turbulent summer environment.

4.2.2.1.3 Distance Constant

4.2.2.1.3.1 Definition of distance constant

ASTM (1985a) defines distance constant as the distance the air flows past a rotating anemometer during the time it takes the cup wheel or propeller to reach (1-1/e) or 63 percent of the equilibrium speed after a step change in wind speed. The step change is specified as one which increases instantaneously from 0 to the equilibrium speed. The step change is simulated by releasing a restrained anemometer in a wind tunnel running at the equilibrium speed. Several authors, among them Acheson (1988), Hayahsi (1987), Lockhart (1987), and Snow et al. (1988), have commented on the difference between the distance constant to an increasing step function and the distance constant to a decreasing step function. The difference is larger with larger and heavier cup wheels, as is the size of the resulting overspeeding error. Snow et al. (1988) point out that a system including a sensor and an analog signal conditioner will have a combination distance and time constant.

4.2.2.1.3.2 Measurement of distance constant

Most manufacturers will provide the distance constant of their product. These are usually derived from tests of prototype sensors during the development phase of the product. The variation from individual to individual in a production model is not large nor important. It is important to use a standard test and standard definitions if distance constant specifications are to be meaningfully compared to other designs and requirements.

EPA (1987a) does not specify a distance constant for anemometers. EPA (1987b) does suggest in the Instrument Procurement section 8.1 a distance constant of <5 m at 1.2 kg/m (standard sea-level density). As with accuracy, this reference uses a footnote to specify the ASTM test method.

The reason why distance constant is included is to urge users to buy high quality responsive sensors. Heavy sensors with long distance constants are more likely to produce overspeeding errors, which overstate the average wind speed. If they are used to measure turbulence, they will underestimate sigma u because of a failure to respond properly to eddy sizes smaller than twice the distance constant.

4.2.2.1.4 Off-Axis Response

This specification, while included in ASTM (1985) and recognized in the literature as a source of error, is not included in EPA requirements or suggestions. It is mentioned here for completeness and in anticipation of future specifications when more data have been published on the subject.

The off-axis errors from helicoid propellers are nearly cosine errors. When a vane-oriented propeller is turned in a wind tunnel so that the wind is at some angle to the axis of rotation of the propeller, the propeller slows down. The indicated speed from this misorientation of the propeller is nearly equal to the total speed times the cosine of the angle of misorientation. That is, if the indicated speed from a propeller is 5.00 m/s and the propeller is being held 10 degrees off the true axis of the flow by the aligning wind vane, the true speed is the indicated speed (5) divided by the cosine of 10 degrees (0.9848) or 5.08 m/s. In natural turbulent flow, a vane located behind the propeller may not keep the propeller perfectly aligned with the wind. Small misalignments result in small errors since the cosine of a small angle is nearly one.

The off-axis errors from a cup anemometer with a properly oriented vertical axis will depend on the design of the cup wheel and the angle from horizontal from which the wind reaches the cups. MacCready (1966) and Kondo et al. (1971) show that cup anemometers overstate the wind speed when the air flow is not horizontal. Kondo shows the overestimation by the cups tested to be 5 percent when the standard deviation of the elevation angle is 17 degrees and 10 percent at 25 degrees. Siting on ridges or building tops or anywhere the distortion of the flow over an object produces a steady non-horizontal flow will result in errors which will be unknown.

The figure from MacCready (1966) showing the response of various anemometers to the elevation angle of the wind is reproduced here as Figure 4.2.2.9.

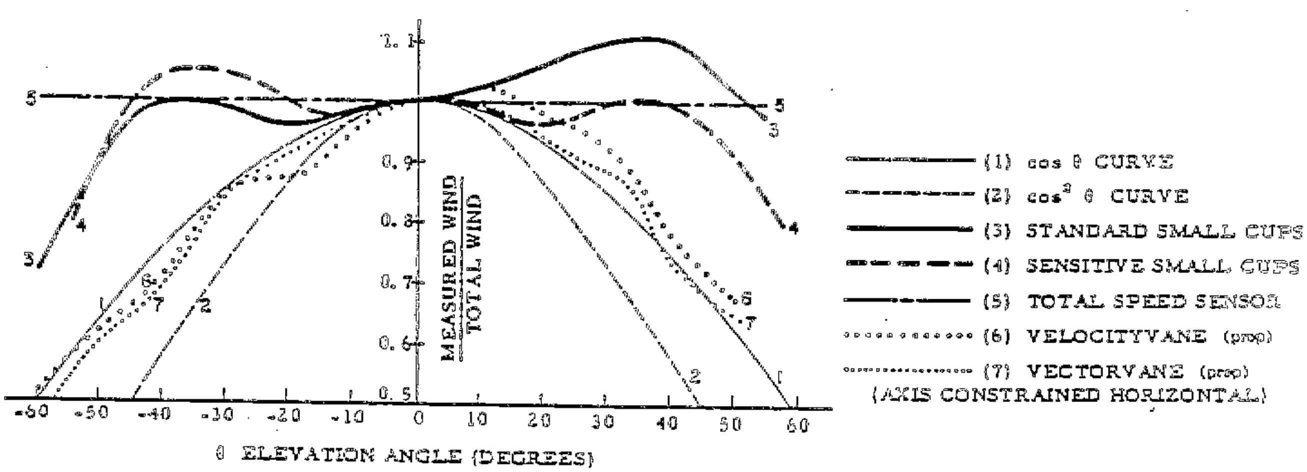


Figure 4.2.2.9 *Anemometer response to off-axis flow*

Consider the fact that a wind of 5 m/s with an elevation angle of 30 degrees will have a horizontal component of 5 x cos (30) = 4.33 m/s. If the presumption is that the cup anemometer is providing the speed of the horizontal component of the wind, and if the cup performs like a "total speed sensor" in the range of ±50 degrees as the figure suggests, the 5 m/s the cup reports is a 15% overestimation of the true horizontal speed of 4.33 m/s. A propeller anemometer will report the horizontal component because it does have a nearly cosine response. Operating side by side in this 30 degree wind, the cup will report 5 m/s and the propeller will report 4.33 m/s and each will be "right."

In addition to the horizontal component dilemma, the cup anemometer tends to overestimate even the total wind. This is particularly noticeable when the air is rising and flows past the support column creating a wake which interferes with the normal cup aerodynamics. The figure shows this effect to be about 10% at +30 degrees for "standard small cups." This 30 degree rising air example suggests that the side by side anemometers mentioned above will really be reporting 5.5 m/s (10% off-axis error for the cup) and 4.33 m/s for the true horizontal speed from the propeller, or a 27% overestimation of the horizontal component by the cup anemometer.

4.2.2.2 Wind Direction

4.2.2.2.1 Threshold

4.2.2.2.1.1 Definition

As with wind speed measurement, a key to a good wind vane for air pollution applications is a low threshold. The threshold is the one performance characteristic which will certainly change with time because of bearing degradation. Most wind vanes use potentiometers to convert position to output voltage. Potentiometers have bearings or bushings which will wear and add to the starting threshold. There is not a standard definition for wind vane threshold, although the ASTM Standard Test Method for DETERMINING THE DYNAMIC PERFORMANCE OF A WIND VANE (ASTM, 1985b) offers the following candidate. The θ_B in the definition is the equilibrium direction of the vane in a wind tunnel at about 10 m/s.

> Starting threshold (S_0, m/s) is the lowest speed at which a vane will turn to within 5° of θ_B from an initial displacement of 10°.

Even this definition runs into some problems in interpretation. If the vane must move at least from 10° to 5° at the threshold speed, is the offset sensitivity really 5° rather than 10°?

The requirement in EPA (1987a) for PSD applications states "Wind direction and wind speed systems should exhibit a starting threshold of less than 0.5 meter per second (m/s) wind speed (at 10 degrees deflection for direction vanes)." Does this mean that a vane that moves from a 10° displacement to 9.5° at 0.5 m/s has a starting threshold of 0.5 m/s? The newer EPA (1987b) on-site guidance says

> "Threshold (1) $\leq$ 0.5 m/s
> (1) as determined by wind tunnel tests conducted on production samples in accordance with ASTM D-22.11 test methods."

The reason the ASTM committee required the vane to move from 10° to 5° was to relate the starting threshold to accuracy. With wind speed, there is a way to correct for threshold nonlinearity; for wind direction there is not. It seemed best to establish the range of operating speeds to correspond to the range where accuracy requirements are met. ASTM assumed 5° for wind direction as a reasonable accuracy.

When torque measurements began their use as a measure of starting threshold, the question became clearer. If the vane is required to move to 5° there should be enough torque developed by the wind speed working on the tail area exposed at 5° from the wind tunnel centerline or the true wind direction to turn the shaft assembly and transducer. This sounds like a 5° threshold requirement, and perhaps that is a better description. As will be shown later, there is a big difference between the torque developed at some speed at 10° and the torque developed at the same speed at 5°. The nature of a standard test method is less important than the application of a standard method everyone uses and regulatory performance requirements consistent with that test method. This handbook will use the 10° offset moving to 5° on release in the wind tunnel (the ASTM method) as the criteria for starting threshold. The relevant torque for this definition is that at 5°.

4.2.2.2.1.2 Threshold measurement

The measurement of starting threshold requires a wind tunnel capable of accurate operation below 1 m/s. One standard methodology is defined in ASTM (1985b) and described in Finkelstein (1981). Just as it is with wind speed, it is possible to measure the torque which results from the force of the wind on a wind vane as the torque measurement device holds the vane at some angle from the wind tunnel centerline, say 10°. Lockhart (1978) describes wind tunnel test data using two very different wind vane designs, the front-damped Meteorology Research, Inc. (MRI) Model 1074 and the more traditional Teledyne Geotech (TG) Model 53.2.

Another body of wind vane torque data exists as a result of tests run by the R. M. Young Company (RMY). Their tests used a DC "torque motor" as the transducer for vanes mounted in their wind tunnel. The torque motor current was linearly correlated to torque measured with a series of Waters Torque Watches. The torque motor drove the vane to each of four positions, plus and minus five degrees and plus and minus ten degrees from the wind tunnel centerline. A measurement of current was taken at each position and at each of 12 wind speeds varying from 0.3 to 6 m/s, depending on the vane design. Table 4.2.2.7 lists the average constant, K, which was found by a linear regression of the motor current (torque) to the square of the wind speed, with the intercept forced to zero. They tested all of their products along with some vanes from other manufacturers.

Table 4.2.2.7 - K Values for Vanes at Two Angles to the Wind

Vane Type	Offset Angle θ				
	5°		10°		
	K	E	K	E	r
Wind Sentry (RMY 03301)	1.8	0.006	3.7	0.017	2.1
Wind Monitor (RMY 05103)	10.6	0.080	23.3	0.114	2.2
Wind Monitor AQ (RMY 05305)	16.8	0.126	37.0	0.260	2.2
Propvane (RMY 08003)	15.9	0.061	38.8	0.304	2.4
Microvane (RMY 12302)	25.0	0.414	57.5	0.760	2.3
Bivane-19 cm fin (RMY 17003)	14.5	0.188	37.6	0.367	2.6
Anemometer Bivane (RMY 21003)	17.1	0.141	45.6	0.457	2.7
Propeller Vane-23 cm (RMY 35003)	19.0	0.127	46.5	0.378	2.4
Long Vane (Vaisala WAV 15)	3.6	0.047	7.8	0.049	2.2
Short Vane (Vaisala WAV 15)	2.0	0.015	4.3	0.029	2.2
Black Aluminum (Met One 024A)	13.8	0.181	28.4	0.394	2.1
High Damping Ratio (Met One024A)	19.9	0.194			
F460 Vane (Climatronics 100075)	16.0	0.322	29.8	0.497	1.9

where: $K = T/U^2$, E = Std. Err. of Coeff. and $r = K(10^\circ)/K(5^\circ)$

The ratio of the 10 degree K value to the 5 degree K value seems to be lower for high aspect ratio vanes. A square vane has an aspect ratio of 1. The Propvane, Microvane, Bivane and Anemometer Bivane are examples of designs with an aspect ratio of 1. A rectangular vane which is two times as high as it is long (along the tail boom) would have an aspect ratio of 2. The Wind Monitors are examples of this design. The F460 vane has an aspect ratio of 4 and a K ratio of 1.9. The "high aspect ratio" TG Model 53.2, whose torque data (natural log of torque vs. natural log of displacement angle) are shown in Figure 4.2.2.10, has an aspect ratio of 6 and has a K value ratio of 1.4 at 0.45 m/s. Differences in torque between 5 degrees and 10 degrees could not be measured at 2.2 m/s (the K value ratio therefore equals one at that speed). The High Damping Ratio (Met One) also has a high aspect ratio and also could not provide a stable torque reading at 10 degrees. The MRI 1074 (aspect ratio of 2) has a K ratio of 2.6. This design is more difficult to compare to other vanes because of its front damping vane.

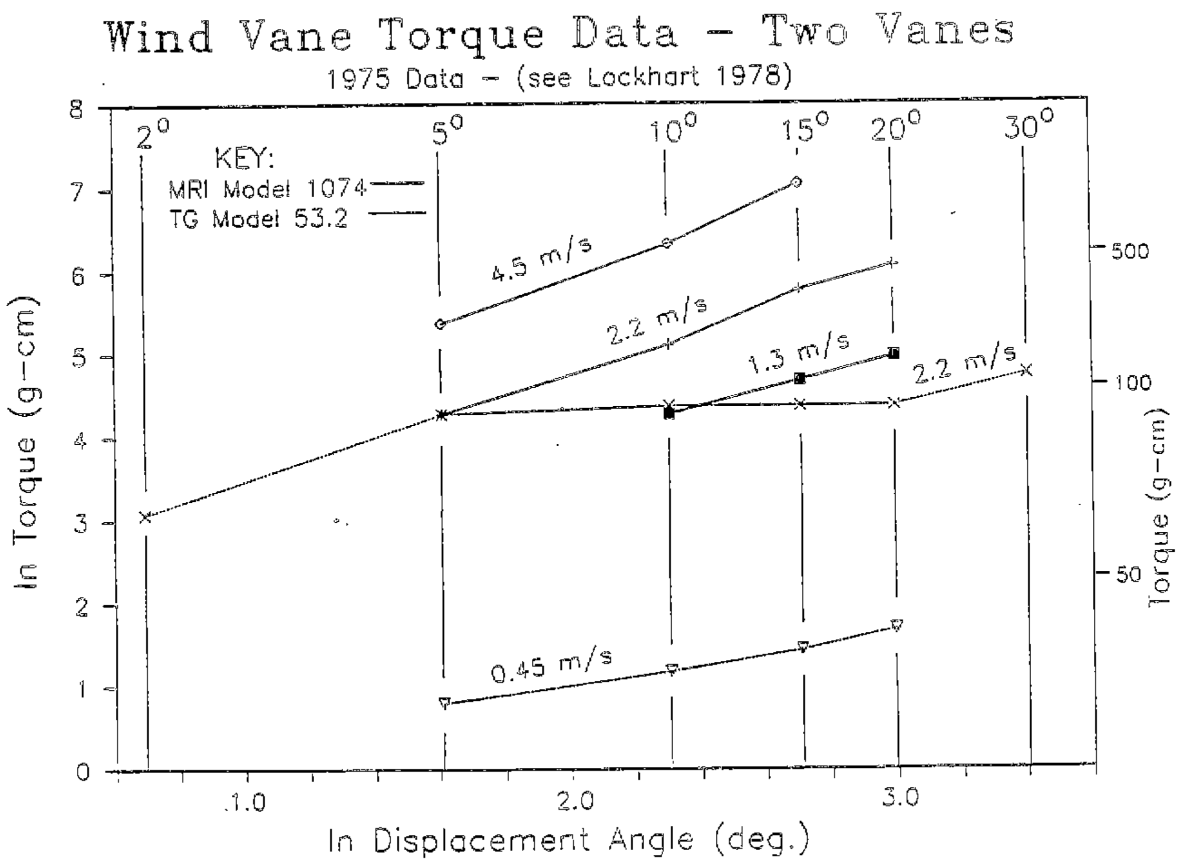


Figure 4.2.2.10 *Torque measurements as a function of vane angle.*

If the starting torque of the shaft of a direction vane bearing and transducer assembly is to be interpreted in terms of wind speed, an expression of torque as a function of speed is required. Each expression is specific to the vane design and an offset angle. Take, for example, the Wind Monitor AQ shown in Table 4.2.2.7. The expression for a 10 degree offset is

$$T = 37\ U^2.$$

If a starting torque were found to be 5.9 g-cm, that measurement can be expressed as a threshold wind speed of 0.4 m/s (0.9 mph). A 0.41 m/s wind at a 10 degree angle from the vane position will produce enough torque to move the vane closer to the wind direction. The expression for this wind vane for a 5 degree offset is

$$T = 16.8\ U^2.$$

The same starting torque of 5.9 g-cm will require a wind speed of 0.6 m/s (1.3 mph) to move the vane closer than 5 degrees to the true wind direction.

Table 4.2.2.8 - Wind Vane Torque vs. Wind Speed and Angle

Wind Speed U (m/s)	Offset Angle θ (deg.)							
	5°		10°		15°		20°	
	T (g-cm)	$\hat{T}_1$ (g-cm)	T (g-cm)	$\hat{T}_2$ (g-cm)	T (g-cm)	$\hat{T}_3$ (g-cm)	T (g-cm)	$\hat{T}_4$ (g-cm)
1.3			72	76	108	97	144	150
2.2	72	69	166	177	324	278	432	430
4.5	216	217	562	557	1152	1163		

T is the measured torque holding the vane at offset angle θ

K is the linear regression coefficient when a = 0

$\hat{T}$ is the predicted torque using K from the following:

$\hat{T}_1 = 19.55\ U^{1.6}$ $\hat{T}_2 = 50.22\ U^{1.6}$

$\hat{T}_3 = 57.47\ U^2$ $\hat{T}_4 = 88.81\ U^2$

The data from Lockhart (1978) for the MRI Model 1074 are shown in Table 4.2.2.8 to demonstrate the complexity of the dynamic performance of some vane designs. A simple expression is useful to convert a torque measurement to a wind speed. The simple vane designs listed in Table 4.2.2.7 fit a U^2 expression quite well. The 5 degree and 10 degree data for the Model 1074 define a different slope than U^2 on the log-log plot of Figure 4.2.2.11. An expression of $U^{1.6}$ fits the data well enough to use to extrapolate the experimental data for this vane design to other wind speeds. The physical reason for this unusual dynamic performance is probably related to the effect of the front damping vane and the relatively large support column. The vortices shed by the column only effect the rear vane.

The question remains, should the 5 degree K value be used or the 10 degree K value? For the purpose of making a conservative estimate of starting threshold for performance accurate to 5 degrees, the 5 degree K value is recommended. The user should not expect this torque-defined threshold to agree with the "starting threshold" published by manufacturers. Only after a test is specified, like the ASTM test, can a 5 degree K value be expected to agree with the data sheet values.

4.2.2.2.1.3 Torque measurement

Starting torque measurements of a wind vane may be made in either of two general ways. If the vane can be removed, a torque watch can be used to measure the starting torque of the bearing assembly and transducer (see Figure 4.2.2.3). For this method to be most accurate, an equivalent weight of the removed vane must be placed on the shaft to simulate the end loads of the shaft of the bearings.

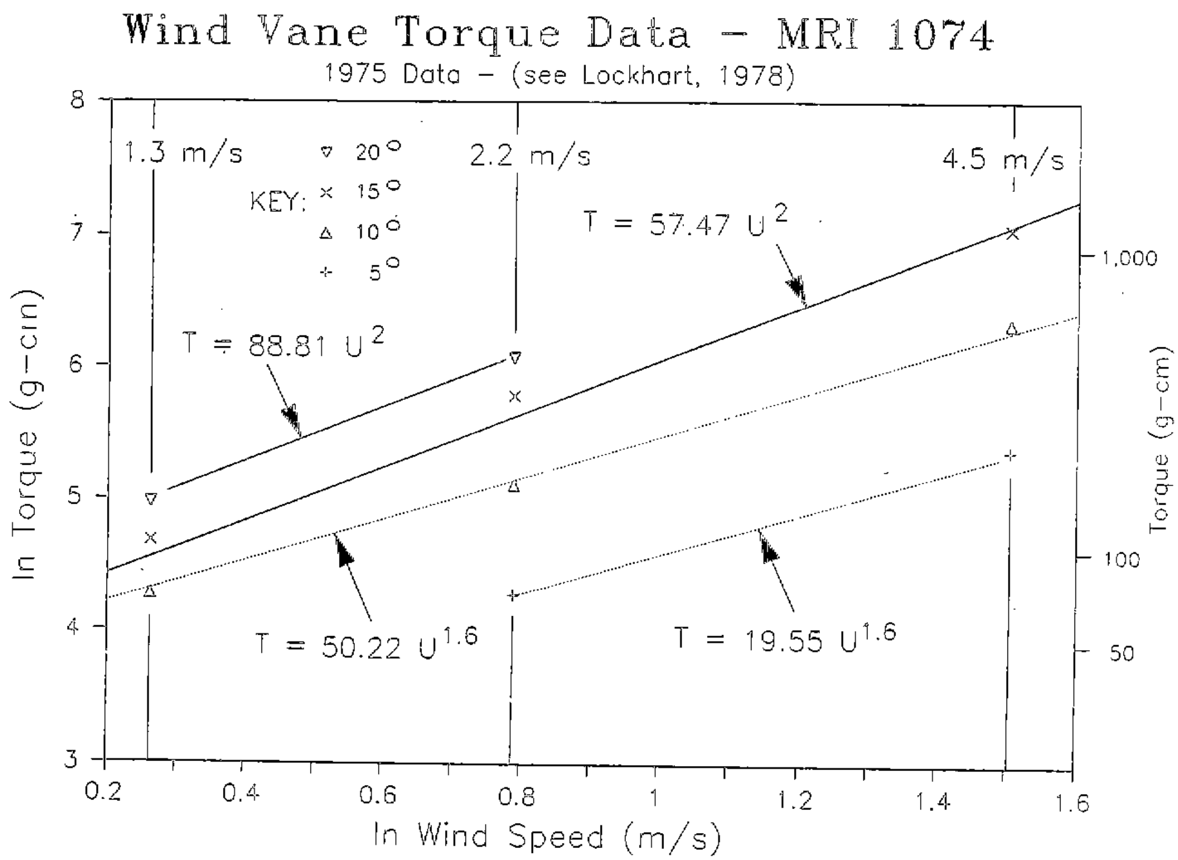


Figure 4.2.2.11 *Torque measurements as a function of wind speed.*

If the vane cannot be removed or the choice is to not remove it, the starting torque can be measured by imposing a force at a measured radial distance from the axis of rotation. A spring-type gram scale at 10 cm from the axis of rotation will yield g-cm after dividing by 10. On some designs it is impossible to impose the force at 1 cm. In the interest of accuracy, it is better to use a longer distance so the length part of the measurement can easily be just a few percent. Of course the trade-off for accurate distance is small force, an equally troublesome source of uncertainty. Figure 4.2.2.12 shows different gram scales used on a Young Wind Monitor AQ.

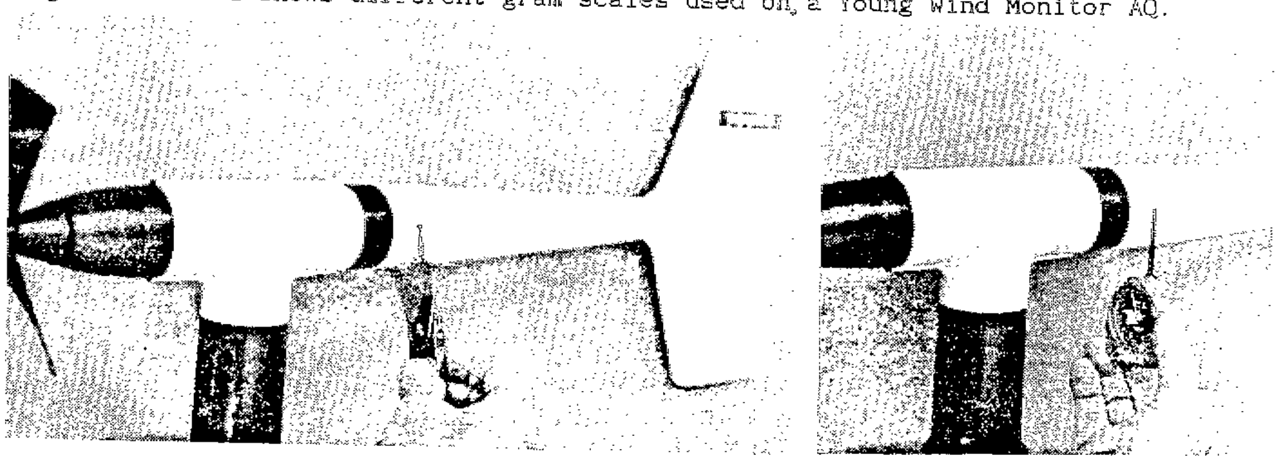


Figure 4.2.2.12 *Starting torque measurements on a wind vane.*

If the vane is left on, the space used for the measurement must be devoid of any air movement. Human breath provides a force which can bias the measurement. It is also important that the axis of rotation be vertical to negate any imbalance in the vane assembly.

For either method, the full 360 degrees of rotation of the vane should be challenged with the highest torque found being reported as the starting torque (worst case).

4.2.2.2.2 Accuracy

4.2.2.2.2.1 Accuracy definition

There is no transfer function for a wind vane comparable to that for an anemometer, unless the conversion of shaft position to output voltage is taken to be such a function. The vane is assumed to be accurately placed, on average, downwind from the axis of rotation, when the wind is steady and its speed is well above the threshold. If the vane is bent in some way, a bias will be introduced (see Dynamic Vane Bias later in this section). This is seldom large enough to be of concern.

The accuracy of the sensor is described by how well the shaft position is reported by the transducer and signal conditioning circuit. The accuracy of wind direction must include the accuracy with which the sensor is sited with respect to TRUE NORTH. Any error in orientation will be a true bias and can be removed from the data at any time the facts become known. The "facts" in this case mean a rigorous quality control program which requires a site log to indicate any servicing of the sensors. The "true bias" can change if the sensor is removed and reinstalled without "as-found and as-left" orientation measurements in the log book. Any possible undocumented change can negate data correction for orientation.

The requirements for accuracy include EPA (1987a) which states "Wind direction system errors should not exceed 5 degrees, including sensor orientation errors." In EPA (1987b) it says

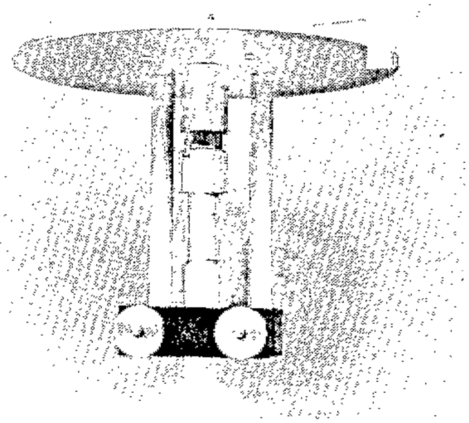
"Accuracy (error)(1) ≤3 degrees relative to the sensor mount or index (≤5 degrees absolute error for installed system)

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

The footnote is in error. There is nothing in the wind tunnel test which relates to wind direction accuracy.

4.2.2.2.2.2 Measurement of sensor accuracy

The simple procedure for this measurement requires some fixture which provides for steps in the direction vane shaft position of known size. There are innumerable devices and methods for this procedure, many of which will be described in the calibration section (4.2.5.2). One device which can move the shaft in 60 degree increments is shown in Figures 4.2.2.13. The important criteria are stability and knowing that the error band for the fixture is on the order of 0.1 degrees of arc.



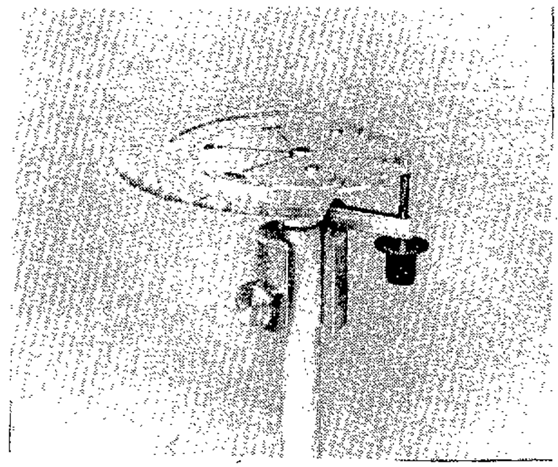


Figure 4.2.2.13 *Wind direction calibration fixtures from Teledyne Geotech (left) and Met. Standards Institute (right).*

Typically, potentiometers used for wind direction will have a linearity of about 0.5 percent, 1.8 degrees in 360 degrees. A table of angles and output values will usually fall within a range between -1.8 degrees and +1.8 degrees when the bias is removed by subtracting the average error from each error. This statement is true when the open sector of the potentiometer is ignored (for 360 degree mechanical and about 352 degree electrical systems, see Section 8.2) or when errors in 540 degree format switching systems are not considered. Other contributions to sensor error, such as hysteresis, out-of-round and signal conditioning errors, when added to the linearity error mentioned above should provide an error band not larger than -3 to +3 degrees relative, or 6 degrees if the bias has not been removed.

An example of audit data shown in Table 4.2.2.9 describes the performance of one wind vane when challenged with a 60 degree fixture. The fixture settings and the displayed digital output ofthe system are listed. The system had a 540 degree range and a 5 volt full scale output. The output is converted to nominal voltage to show how the 540 range works. (Degrees per volt = 540 / 5 = 108)

The average error of -3.4° was calculated without using the obvious "open section" values marked by "*." When the fixture is installed the vane substitute is set in the 180° location and then rotated until the output is about 180. This need not be precise since the average error provides a means of normalizing the data by removing the initial bias of approximate setting. The linearity of the potentiometer-signal conditioner can be seen in Figure 4.2.2.14. Except for the "open sector" near 360°, the error is within a $\pm 3^\circ$ band, including the 540° format switching error of about 1°.

Table 4.2.2.9 - Relative Wind Direction vs. Output Direction

Fixture Setting A (deg.)	System Output B (deg.)	Nominal Voltage B/108 (volts)	Error E=B-A (deg.)	Normalized Error E-C (deg.)	Normalized Output B-C (deg.)
180 ccw	177	1.639	-3.0	0.4	180.4
120 ccw	114	1.056	-6.0	-2.6	117.4
060 ccw	054	0.500	-6.0	-2.6	057.4
360 ccw	001	0.009	1.0*	4.4*	005.4
300 ccw	298	2.759	-2.0	1.4	301.4
240 ccw	238	2.204	-2.0	1.4	241.4
180 ccw	176	1.630	-4.0	-0.6	179.4
120 ccw	115	1.065	-5.0	-1.6	118.4
180 cw	177	1.639	-3.0	0.4	180.4
240 cw	239	2.213	-1.0	2.4	242.4
300 cw	292	2.704	-2.0	1.4	301.4
360 cw	001	3.343	1.0*	4.4*	005.4
060 cw	056	3.852	-4.0	-0.6	059.4
120 cw	115	4.398	-5.0	-1.6	118.4
180 cw	177	4.972	-3.0	0.4	180.4
240 cw	239	2.222	-1.0	2.4	242.4

average error C = -3.4 (* values excluded)
cw is clockwise, ccw is counterclockwise

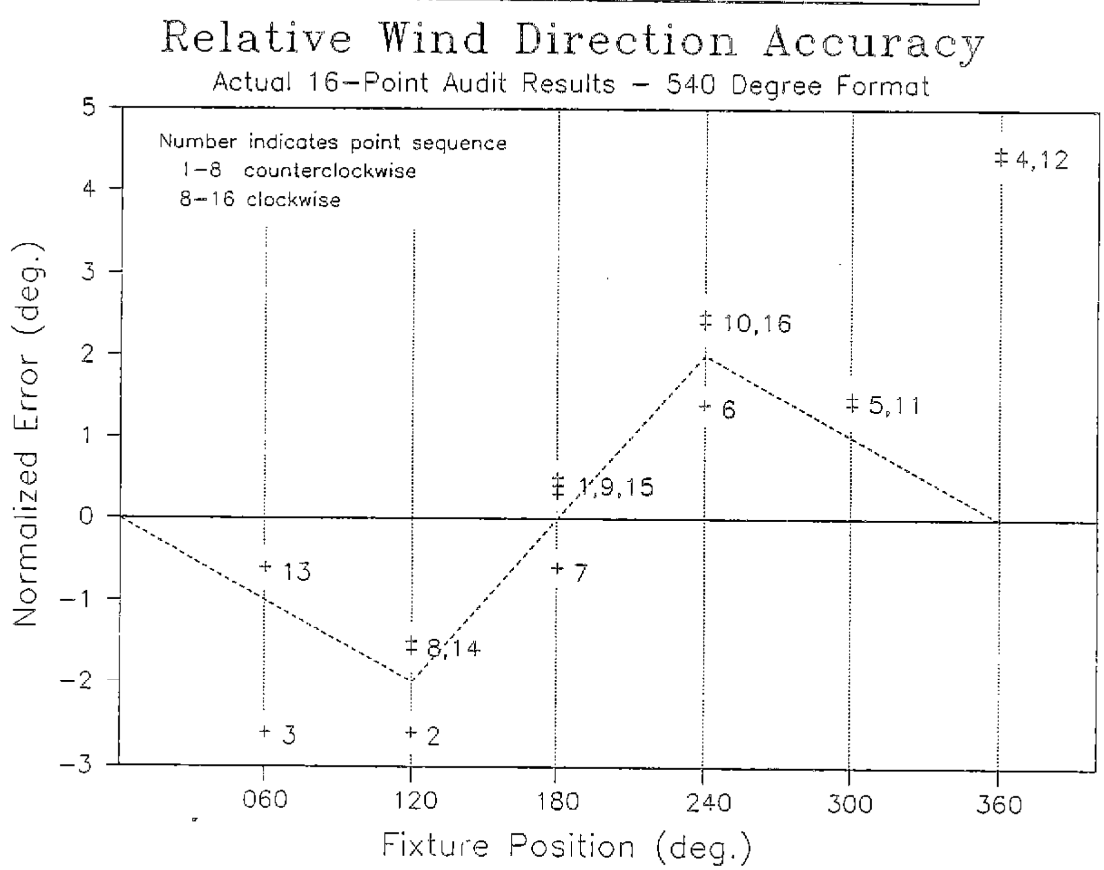


Figure 4.2.2.14 *Results of a wind vane audit using 60° steps.*

An analysis of this type helps to optimize the accuracy of the orientation. If an orientation target is at 120° TRUE, when the vane is pointing from 120° the output should read about 118°. This effectively centers the error band (see 4.2.4.3.2 on orientation).

4.2.2.2.2.3 Measurement of orientation accuracy

Orientation error is an important part of the measurement error, but it cannot be considered until the sensor is installed in the field. The accuracy of the orientation includes the accuracy in finding TRUE NORTH and the accuracy with which the vane is aligned to TRUE NORTH. Use different methods for finding TRUE NORTH. Methodology for orientation is given in 4.2.4.3.2.

4.2.2.2.2.4 Expression of Accuracy

An accuracy specification should include enough information to define the type of accuracy intended and the method by which accuracy claims may be tested. There is no requirement for traceability to NBS for wind direction. The measurement of relative direction is a fundamental division of a circle. The measurement system can be bench tested by basic methods yielding a clear expression of the errors associated with a position angle vs. system output transfer function. The errors are mostly conditional biases which are small enough (less than one percent of 360 degrees) to ignore.

The orientation error is a pure bias which cannot be bench tested. The total error, a simple sum of the two parts (root-sum- square, RSS, combination is only legitimate with random errors, not biases), can only be found after installation.

4.2.2.2.2.5 Precision

The definition of accuracy describes a bias term and a variable term akin to precision. A comparability test (see 4.2.2.1.2.4) will show that two vanes properly sited and perfectly oriented will report the 20 minute scalar average directions with a difference of less than two degrees, i.e. precision is ± 2°.

An expression of accuracy for a wind vane operating on a 10 m tower in the atmosphere can be expressed as the relative accuracy plus orientation accuracy and ± 2° for precision. For a collocated test (Lockhart, 1988), the orientation error can be estimated by the average difference between the subject wind vane and a collocated wind vane perfectly oriented. If the orientation error is found to be large, and if a quality control system has provided records of maintenance showing the orientation has not been changed, a bias correction can be applied. The accuracy of the data corrected for bias is then the relative accuracy ± 2°.

4.2.2.2.3 Delay Distance (Distance Constant)

4.2.2.2.3.1 Definition of delay distance

ASTM (1985b) defines delay distance (D) as the distance the air flows past a wind vane during the time it takes the vane to return to 50 percent of the initial displacement. The value for this sensor specification is found in wind tunnel tests, as described in Finkelstein (1981). The initial displacement is 10 degrees and D is the average of a series of tests at 5 m/s and 10 m/s using displacements on both sides of the tunnel centerline.

The specification in EPA (1987a, PSD) says "...the distance constant should not exceed 5 m." In EPA (1987b, On-Site) the specification says

"Delay Distance (1) ≤5 m at 1.2 kg/m^3 (standard sea-level density)

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

4.2.2.2.3.2 Measurement of delay distance

Measurement requires a wind tunnel of reasonable size and quality. The width of the tunnel should be at least three quarters of the overall length of the wind vane to be tested. With the small displacement angle of 10 degrees (about 3 percent of full scale), it is hard to conduct this test in the open atmosphere.

This specification is strictly a sensor dynamic performance specification. Any time constants in the signal conditioning circuits will dampen the apparent sensor response and make D larger than it is for the sensor. One could argue that it is ONLY the combination of D and the time constant of the signal conditioner that should be considered in meeting the regulatory requirements for performance. The 5 m maximum for D is roughly equivalent to a time constant of 0.5 seconds at 10 m/s wind speed and a 1 m vane. For this and other reasons it is best to keep the time constant of the signal conditioning circuits to 100 ms or less. For the same reason, it is necessary to use high speed recording equipment for the wind tunnel tests. At 10 m/s, a 1 m vane reaches the 50 percent D value in 100 ms. If one wants resolution to find D to 10 percent of the true value (0.1 m), a 5 ms resolution in the data is desirable.

4.2.2.2.4 Overshoot or Damping Ratio

4.2.2.2.4.1 Definition of overshoot or damping ratio

ASTM (1985b) defines Overshoot (Ω) as the ratio of the amplitudes of two successive deflections of a wind vane as it oscillates about θ_s after release from the offset position, as expressed by the equation

$$\Omega = \frac{\theta_{(n+1)}}{\theta_n}$$

where θ_n and $\theta_{(n+1)}$ are the amplitudes of the n and (n+1) deflections, respectively.

The Damping Ratio (η) may be calculated approximately from the overshoot ratio by the formula

$$\eta \cong \frac{\ln\left(\frac{1}{\Omega}\right)}{\sqrt{\pi^2 + \left[\ln\left(\frac{1}{\Omega}\right)\right]^2}}$$

The specification in EPA (1987a, PSD) says "The damping ratio of the wind vane should be between 0.4 and 0.65..." In EPA (1987b, On-Site) the specification says

"Damping Ratio (1) ≥0.4 at 1.2 kg/m^3 or

Overshoot (1) <25% at 1.2 kg/m^3

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

The subject of dynamic wind vane performance is thoroughly discussed in MacCready and Jex (1964), Gill (1967), Weiringa (1967) and Acheson (1970).

4.2.2.2.4.2 **Measurement of overshoot**.

The measurement of overshoot also requires a good wind tunnel and sensitive, fast response recording systems. A series of tests were conducted by Lockhart in 1986 in pursuit of a wind vane design with a 0.6 damping ratio. A sketch of the results of this unpublished work is shown in Figure 4.2.2.15 to provide an example of how various vane designs compare in overshoot and delay distance. One of the requirements in the ASTM method is an initial offset of 10 deg.

4.2.2.2.5 Dynamic Vane Bias

The Dynamic Vane Bias (θ_B, deg.) is the displacement of the vane from the wind tunnel centerline at 5 m/s. This measurement will identify wind vanes with unbalanced aerodynamic response because of damage (bent tail) or design. This is a screening specification not needed or used in any application requirements. The ASTM method measures this difference, if any, and disqualifies the vane if the difference is greater than one degree.

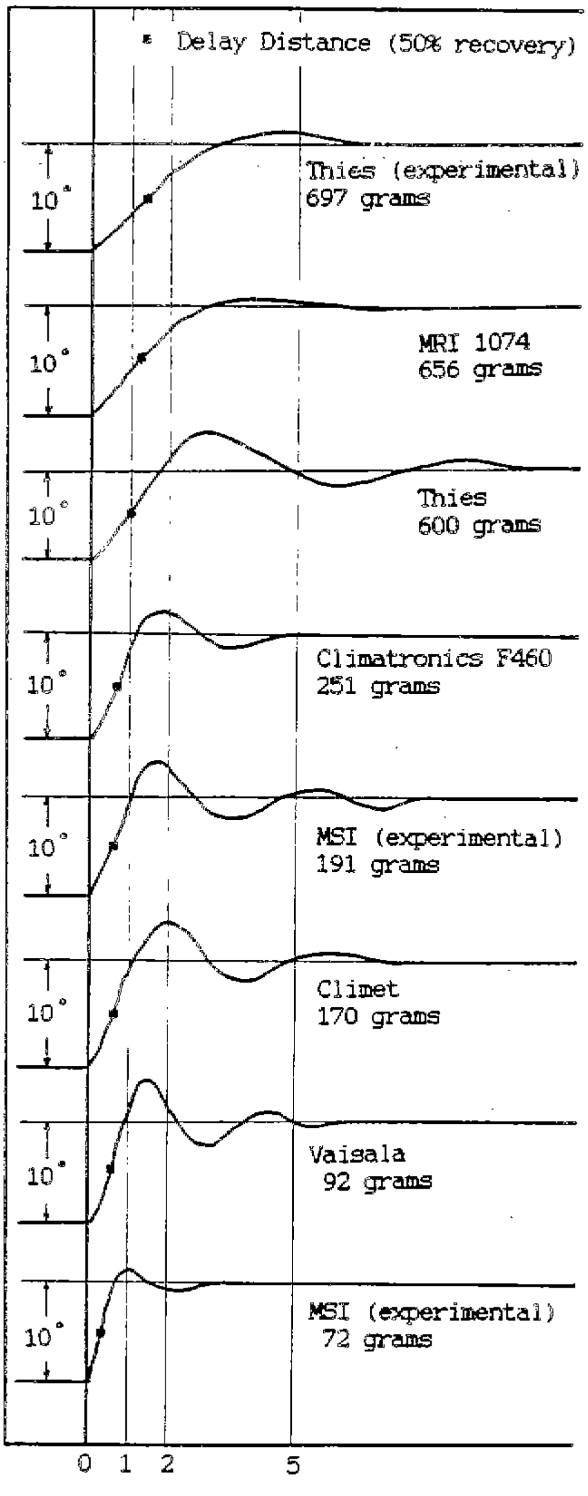
4.2.2.3 TURBULENCE

4.2.2.3.1 **Definition**

The Glossary of Meteorology (Huschke, 1970) quotes Sutton (1955) defining turbulence as a state of fluid flow "in which the instantaneous velocities exhibit irregular and apparently random fluctuations so that in practice only statistical properties can be recognized and subjected to analysis. The situation is, in fact, analogous to that accepted unreservedly in the field of molecular physics..." The definition is ended with a quote from the Bible"

The wind bloweth where it listeth and thou hearest the sound thereof but canst not tell whence it cometh and whither it goeth:... John 3:8

From the standpoint of wind measurement, then, turbulence is not measured, it is calculated. From the standpoint of quality assurance, turbulence is a difficult subject to control. It is possible to define the measurement samples from which the statistical properties are calculated. It is possible to define the algorithm by which the samples are summarized. The relationship between the algorithm and the application or model is also important, but it is beyond the scope of this handbook.



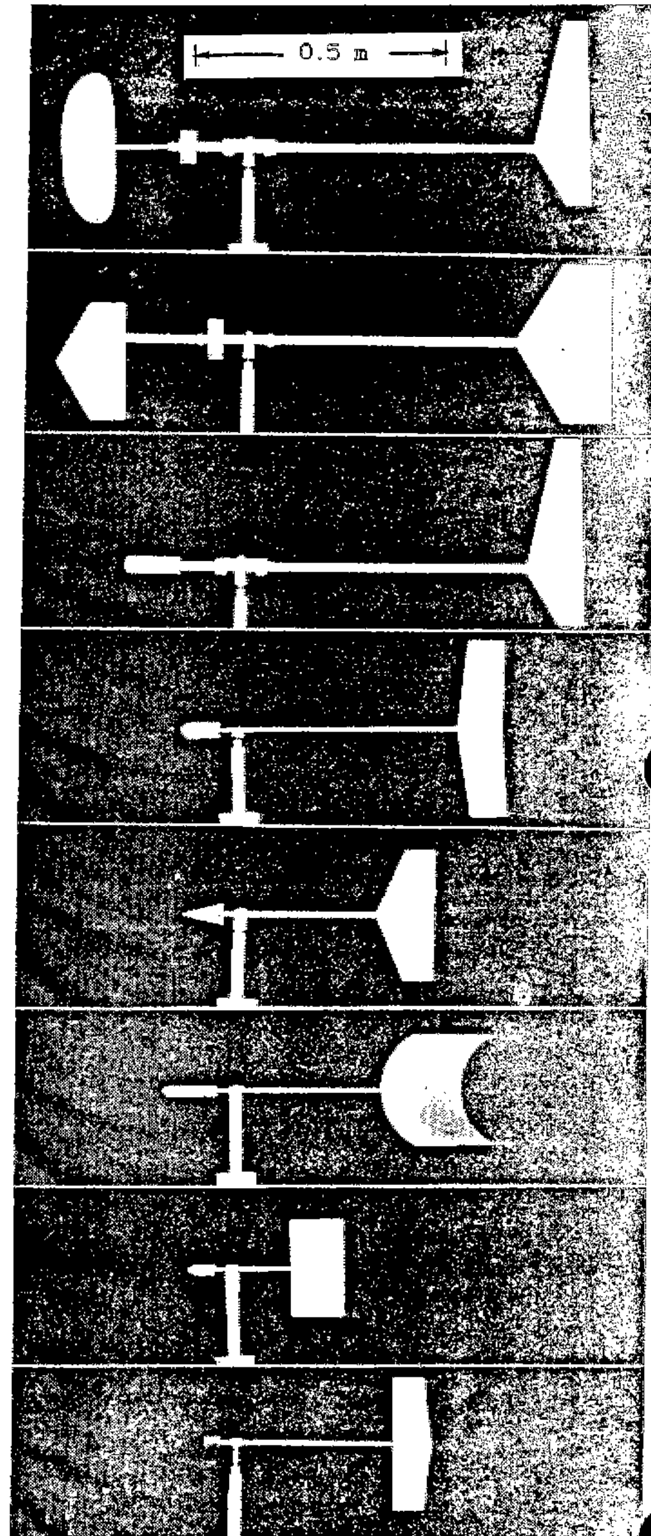


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Figure 4.2.2.15 *A sample of the dynamic response of some wind vanes*

4.2.2.3.2 Direction Measurement for Sigma Theta

The most common turbulence property routinely reported is sigma theta, the standard deviation of a series of horizontal wind direction samples. Most, but not all, of the following will also apply to sigma phi, the standard deviation of a series of vertical wind direction samples. Among the specifications which are important to the direction measurement used to calculate sigma theta is delay distance which limits at the small end of the eddy size spectrum the eddy sizes to which the vane can react. If the vane has a delay distance of 5 m, it will not detect energy from eddys smaller than 5 m because the vane cannot react to them. If 1 m eddy sizes are important to the diffusion being estimated, use a wind vane having a delay distance of 1 m or less.

Another important specification is overshoot or damping ratio. Vanes will overshoot when correcting for a direction change. If the overshoot ratio is 0.5 (or 50%), more variability will be reported from the same turbulent flow than is reported by a vane with an overshoot ratio of 0.25 (or 25%). The relationship between overshoot ratio and damping ratio is given in Table 4.2.2.10 as calculated by the equation found in 4.2.2.2.4.1.

Table 4.2.2.10 - Overshoot Ratio vs. Damping Ratio

Overshoot Ratio	Overshoot Percent	Damping Ratio
1.00	100	0.00
0.90	90	0.03
0.80	80	0.07
0.70	70	0.11
0.60	60	0.16
0.50	50	0.22
0.40	40	0.28
0.35	35	0.32
0.30	30	0.36
0.25	25	0.40 ¦
0.20	20	0.46 ¦
0.15	15	0.52 ¦
0.10	10	0.59 ¦
0.05	5	0.69

¦ denotes PSD range

Sigma calculations are biased by any averaging built into the signal conditioner. They are also subject to error if external noise gets into the output, a dilemma for circuit designers. A compromise might be to filter out any noise at frequencies higher than 20 Hz (0.5 m at 10 m/s). In winds above 20 m/s, this filter would degrade data from a wind vane having a delay distance of 1 m. Turbulence from mounting structures upwind of the vane will bias the sigma value. Out-of-balance conditions with a vane measuring sigma phi will also bias the statistic, particularly at the low wind speeds. Un-filtered noise from potentiometers will add an error to the natural variability of the wind. These are problems which are best detected by inspection of strip charts or oscilloscope traces.

4.2.2.3.3 Statistical Summaries

A few basic concepts will help in considering the specifications of the statistical algorithm used and the representativeness of the value calculated. Here again, careful definition will help understand what the circuits and logical networks are doing to the input samples. EPA (1987b) devotes 44 pages to Meteorological Data Processing Methods.

Representativeness is the important concept to keep in mind when examining strange or unusual data. Samples of wind direction taken over a short period of time (seconds to a minute or two) are likely to exhibit nearly normal or Gaussian distribution. As the time gets longer (a few minutes to an hour or more), physical dynamics driving the flow in the surface layer may provide different shapes. The most common of these might be the bi-modal distribution resulting from land-water, mountain-valley, day-night or meso-scale convective flow systems. Whatever the driving forces, a bi-modal distribution cannot be usefully represented by a mean and standard deviation. This is to say that a data sampling and processing system may work perfectly and produce numbers which have no physical meaning. From a specification standpoint, tests for "working perfectly" are possible and should be used.

The method used by the wind direction system to describe the position of the vane in the series to be statistically described must be thoroughly described and understood. The most common error in the past, perhaps even made today, is to do nothing. If the output voltage unambiguously represents an azimuth angle, and if samples of voltage are described with the statistical parameters of mean and standard deviation, and then expressed in units of azimuth angle, great errors will result. These errors are a result of a discontinuous range of output voltage. If 001-360 degrees are represented by 0-1 volt, samples clustered around 360 will contain some near 0 and some near 1. The mean of 0.5 will be 180 degrees away from the mode.

When analog ink recorders were used exclusively with 360 degree formats, it was common to see the paper painted red by the pen going back and forth through full scale, effectively obliterating any data. There are several ways to avoid or minimize the "crossover" problem. System specification should define how this will be done. The most common method for minimizing this error is to use a "540 degree" format. Systems were designed with dual potentiometers or dual wipers 180 degrees out of phase. When the wiper moved into the gap, circuit switching would change to the center of the other circle. This switching would be invisible in the output at the 1/3 and 2/3 scale points, but when the voltage went beyond full scale, it would switch to 1/3 scale and when the voltage went to zero, it would switch to 2/3 scale. This format completely eliminated the pen painting problem and drastically reduced the output voltage switching, but some large pulses remained to occasionally bias sigma calculations.

With the advent of microprocessors and digital computers it became possible to combine the samples without any large pulses. One method uses a unit vector sum to find the resultant vector direction (average direction). With an assumed wind speed of 1 m/s, each sample of wind direction is converted from polar coordinates (001-360 degrees) to cartesian coordinates (N-S and E-W components in meters). The components are added or subtracted over the sample period and the resultant vector direction is found by converting the final coordinate sums to polar coordinates through an arc-tangent calculation. The standard deviation of each sample about the resultant vector direction is a straight forward process on the differences of the samples from the "average." Of course, this same method can be used with the true speed-weighted wind vector samples.

Some automatic systems currently available pick an assumed direction, usually the mean of the last period, take the digital difference in degrees (limited to 180) of each sample from the assumed mean, and find the standard deviation and the mean difference for the period. The standard deviation about the mean is the same as the standard deviation about the mean plus a constant. The mean difference plus the assumed direction is the true mean (limited to 360 degrees).

There are also other algorithms which estimate the standard deviation (see Turner, 1986). It is only necessary from the standpoint of quality assurance to know that the method used is being satisfied with the samples taken from the measurement system.

The sample size is specified in EPA (1987b) as 360 samples to estimate the standard deviation to within 5 or 10%. Lockhart (1988) found an apparent bias, not a random error, when the standard deviation was estimated from 120 samples over a 20 minute period.

Most models accept data representing one hour. Sigma theta for 60 minutes is influenced by the changing wind direction during the hour. It is recommended (EPA, 1987b) that four 15-minute sigma theta calculations be combined to provide a "one hour" value for the purpose of selecting a Pasquill-Gifford stability class. The method is

$$\sigma_{A(1-hr)} = \left[\frac{\sigma^2_{A_{15}} + \sigma^2_{A_{30}} + \sigma^2_{A_{45}} + \sigma^2_{A_{60}}}{4} \right]^{\frac{1}{2}}$$

where $\sigma^2_{A_{15}}$ is calculated between 00 and 15 minutes,

where $\sigma^2_{A_{30}}$ is calculated between 15 and 30 minutes,

where $\sigma^2_{A_{45}}$ is calculated between 30 and 45 minutes,

where $\sigma^2_{A_{60}}$ is calculated between 45 and 60 minutes,

where each σ^2_A is a 15 minute standard deviation of wind direction. The proper label for this average value is $\sigma_{A(\overline{15})}$, since it is the square root of the average 15-minute variance and contains no energy from eddy sizes larger than the 15-minute period. Any change in mean direction from one period to the next is excluded from this value but included in the true standard deviation of the direction about the hourly mean. If the standard deviation about the hourly mean is required for a concentration distribution analysis, the correct formulation for $\sigma_{A(1\text{-hr})}$ is shown below.

$$\sigma_{A(1\text{-hr})} = \left[\frac{n_1\sigma_{A_1}^2 + n_2\sigma_{A_2}^2 + n_3\sigma_{A_3}^2 + n_4\sigma_{A_4}^2 + n_1 d_1^2 + n_2 d_2^2 + n_3 d_3^2 + n_4 d_4^2}{n_1 + n_2 + n_3 + n_4}\right]^{\frac{1}{2}}$$

where n_1, n_2, n_3, n_4 are the number of samples in periods 1,2,3 and

and $d_1^2, d_2^2, d_3^2, d_4^2$ are calculated for each period from

$$d_1 = \bar{A}_1 - \bar{A}$$

$$d_2 = \bar{A}_2 - \bar{A}$$

$$d_3 = \bar{A}_3 - \bar{A}$$

$$d_4 = \bar{A}_4 - \bar{A}$$

where $\bar{A}_1$ is the average direction for period n_1 etc.

and $\bar{A}$ is the average direction for all four periods.

See Box et al. (1978) for further discussion of the calculation of total variance from discrete subset variances and means.

4.2.3 ACCEPTANCE TESTING

The procurement document, purchase order or contract, should be specific at least in terms of required performance specifications. "Required" in this context may only mean that the instrument meets the suggested or specified regulatory performance. It is another question, beyond the scope of this handbook, whether "necessary" relates to the application to which the data will be used.

There are two kinds of performance specifications, those which can be verified by simple inspection testing and those which require unusual test equipment and experience. The former should be tested and the latter certified by the manufacturer. The manufacturer should have either performed these tests on one or more samples of the model design or arranged for such tests to have been conducted by some calibration facility. In either case, a test report should be available to any who require the documentation. The cost of the copy of the test report should not be much larger than the cost of normal copying. If the manufacturer does not provide such documentation, the choice is between accepting the manufacturer's unsubstantiated claim or having a specific test run.

A good QA Plan will provide for a QA sign-off of the procurement document in order to assure that equipment capable of the required performance is being purchased and that the capability can be verified. Purchasing by brand name is often expedient where the performance of a model has been verified and all that is required is more units. This practice is also cost effective when considering spare parts and instrument technician training costs.

The parts of wind speed and wind direction sensors which predictably deteriorate and seriously influence the performance of the sensors are the bearings. It is acknowledged that an experienced inspector can "measure" bearing condition by feeling or spinning the shaft. The receiving inspection is a protection against putting defective equipment into the field. It is not a necessary link in the documentation trail for data validity purposes. True torque measurements for data validity will be most valuable at the initial field calibration. True laboratory conditions may be chosen, however, because torque measurements are sufficiently difficult to make.Therefore, a receiving inspection may be used for this purpose.

4.2.3.1 Wind Speed

An example is found in Table 4.2.3.1. This performance specification for an anemometer is hypothetical but one which will meet the requirements of EPA (1987a, PSD). Each attribute of the instrument is identified by a key as to whether it is a receiving test candidate of not, and the nature of the testing is briefly discussed below. Each instrument includes a sensor, signal conditioner, and recorder. When an attribute of the sensor is affected by the signal conditioner or recorder, a keyed comment will be made.

Table 4.2.3.1 - Anemometer Performance Specification

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

(†) as determined by wind tunnel tests conducted on production samples in accordance with ASTM D-22.11 test methods (ASTM, 1985a).

(‡) aerodynamic shape (cup or propeller) with serial number to be accompanied by test report, traceable to NBS, showing rate of rotation vs. wind speed at 10 speeds with 0.1 m/s resolution.

1 subject to receiving inspection
2 transducer with signal conditioner

4.2.3.1.1 Threshold

The threshold receiving test should examine the system output with the anemometer not turning (below sensor threshold) and with the anemometer turning at an equivalent 0.5 m/s. If the cup is a Climatronics F460 Vinyl Cup Set (100083) or Heavy Duty Cup Set (101287), the published constant for mph and 30 pulses per revolution is 9.511 which converts to 1.41 meters per revolution. At 0.5 m/s the cups should be turning at

$$0.5 \div 1.41 = 0.35 \text{ rps},$$

or one revolution in 2.8 s. The cup assembly can be turned by hand to approximate that rate of rotation. If the anemometer is a Young propeller (08234, 18 cm polypropylene), the turning factor is 0.294 meters per revolution. At 0.5 m/s the propeller should be turning at

$$0.5 \div 0.294 = 1.70 \text{ rps},$$

or two revolutions in 1.2 s. This also can be approximated by turning the propeller by hand.

The key measurement for threshold, however, is starting torque. This requires knowledge of the K value (see 2.1.1.2) which should be available from the manufacturer.

4.2.3.1.2 Accuracy

The receiving test for accuracy is the conversion of rate of rotation to output in units of wind speed. The transfer function, supplied by the manufacturer, should be in terms of rate of rotation (rps) vs. wind speed (mps). The receiving inspector simply turns the anemometer shaft at a few known rates of rotation to see if the systemoutput compared to the predicted output is within the tolerance specification.

4.2.3.1.3 Distance constant

The distance constant determination requires a special wind tunnel test and is beyond normal receiving inspection capability. The time constant of the anemometer circuitry will influence the effective system performance. Assume the manufacturer's value for distance constant of the sensor is one meter. At a wind speed of 10 m/s the sensor will have a time constant of 0.1 s. Assume the time constant of the system electronics is 2 s. Then, at a wind speed of 10 m/s, the system time constant is 2 s or 20 m. In this example, the system electronics would need a time constant of 0.1 s or less if the response capability of the sensor is to be fully available. At a wind speed of 0.5 m/s the sensor responds in 2 s, the same as the system electronics. In this example, the system electronics dominates the sensor response at all speeds. If the sensor response is to be available at all speeds (up to 25 m/s), the electronics time constant must be 0.04 s or less. The time constant can be measured at the receiving test by timing how long it takes for the output to reach 63.2% (1-1/e) of a step change in speed. The step change can made by turning the anemometer shaft at a known rate of rotation and then instantaneously stopping its rotation.

4.2.3.2 Wind Direction

An example of a wind direction specification is found in Table 4.2.3.2 (see EPA, 1987b). This performance specification is also hypothetical but it is one which will meet the requirements of EPA (1987a, PSD). Each instrument includes a sensor, signal conditioner, and recorder. When an attribute of the sensor is affected by the signal conditioner or recorder, a keyed comment will be made.

Table 4.2.3.1 - Wind Vane Performance Specification

Range [1]	001 to 360 degrees or 001 to 540 degrees
Threshold [1,2] (†)	≤ 0.5 m\s
Accuracy (error) [1,2] (†)	≤ 3 degrees relative to the sensor mount or index - ≤ 5 degrees relative to TRUE NORTH
Delay Distance [2] (†)	≤ 5 m at 1.2 kg/m^3 (standard sea level density)
Damping Ratio [2] (†)	≥ 0.4 at 1.2 kg/m^3
Overshoot [2] (†)	≤ 25% at 1.2 kg/m^3

(†) as determined by wind tunnel tests conducted on production samples in accordance with ASTM D-22.11 test methods (ASTM, 1985a).

1 subject to receiving inspection
2 transducer with signal conditioner

4.2.3.2.1 Threshold

The threshold receiving test is a starting torque measurement (see 4.2.2.2.1). To relate the torque measured to wind speed and off-set angle, a K value is required, either from the manufacturer or from an independent test. The torque measurement may be made with the vane assembly removed or with the vane assembly in place. If the latter is chosen, verticality is essential to negate any out-of-balance in the vane assembly from biasing the test. Also there must be no air motion. Very small air motions will bias the test. Use a smoke puff to be sure the air is still and refrain from breathing in the direction of the vane surface.

4.2.3.2.2 Accuracy

The receiving inspection is the best place to establish the true non-linearity, if any, of the direction vane transducer. A test using some circle dividing fixture capable of fine resolution, 1 deg. for example, will provide a record which can be referenced in future field spot checks. Without such a test it is hard to prove accuracy of ≤ 3 deg. If several units show the same pattern of non-linearity, it should be acceptable to sample future units and accept a generic shape of the error. When a long series of samples is planned, there is a tendency to devise methods which are quick. The time constant of the signal conditioning circuit must be known to establish the minimum time between position change and output reading or recording. If the step is small, like 1 deg., three time constants will deliver 95% of 1 deg., which is good enough. If the step is large, like 180 deg., three time constants will deliver 95% of 180 or 171 deg. which is not good enough. It takes seven time constants to deliver 99.9% or 179.8 deg.

The receiving inspection cannot include the orientation error. The manufacturer does not deliver orientation. There may be orientation fixtures, however, which assume that an optical centerline is parallel to the line set by an orientation pin. This assumption can be tested. Field orientation may be based on the orientation of a crossarm with the assumption that the output angle when the vane is parallel to the crossarm is known. This assumption can be tested or the alignment fixture set in laboratory conditions to the desired output.

4.2.3.2.3 Delay distance and overshoot

These dynamic characteristics require a special wind tunnel test and their determination is beyond normal receiving inspection capability. The time constant of the wind direction circuitry can influence the system performance as it can with wind speed. Assume the manufacturer's value for delay distance is one meter and the time constant of the electronics is 2 s. At wind speeds of 10 m/s the time constant of the wind vane is 0.1 s and at 0.5 m/s it is 2 s, the same as the system electronics. For this example, therefore, at all speeds above 0.5 m/s the performance of the wind vane is being limited by the time constant of the electronics. The time constant can be measured at the receiving test by timing how long it takes for the output to reach 63.2% (1-1/e) of a step change in direction. For example, the step change can made by quickly turning the vane from 000 to 180 deg. The time constant is the time required for the system output to change from 000 deg. to 113.8 deg.

4.2.3.3 Measurement System

All the elements of a system of signal conditioners, recorders and monitors will require checking for correct function. The receiving inspection should include testing these various sub-systems. There may be a calibration switch which replaces the sensors with simulated conditions. Assume a system has a calibration switch which substitutes the equivalent of 25 m/s and 180 deg. to the input of the signal conditioning boards. In 4.2.3.1 and 4.2.3.2 the sensors were providing the input values. It is possible for these tests to show perfect results and yet the outputs with the calibration switches on could show the system to be out of calibration. The reason would be that the adjustments for the substitute calibration inputs were off.

After the calibration inputs have been adjusted and the "output" shows the system to be in calibration, a parallel analog recorder may show incorrect values. This event could be caused by an incorrect adjustment in the interface which drives the analog recorders from the output. So far the "output" is assumed to mean the voltage which goes into the data logger and becomes the archived data. There may be monitoring meters or digital displays on the system panel. These monitoring meters may differ from the "output" because they have individual adjustments. All the sub-systems should tell the same story and the receiving inspection should verify that they do. In fact, it is rare when a system arrives in receiving with the various outputs in disagreement, but they must be checked.

It goes without saying that the receiving function records the model numbers and serial numbers of the component parts and checks the parts received against the purchase document and the shipping document.

4.2.4 INSTALLATION

4.2.4.1 General Considerations

From a QA point of view, there are aspects of the installation which should be considered. Perhaps the most important of these is siting. See 4.0.4.4 for general siting criteria and discussion. From a QA point of view, however, failure to meet the recommended siting criteria may be necessary. If the general site is selected for other measurements for good reason, the wind sensor siting may be only a best compromise. There are considerations which set the options for the compromise. Among these are technical and budgetary considerations. The qualitative judgments which go into siting are briefly discussed here.

If buildings or trees are likely to interfere with the wind speed or direction sensing, try to locate the tower or pole such that the wind sensors will most faithfully record speed and direction for the direction of primary concern, e.g. for directions that would take an effluent toward a residential area.

Another important technical consideration is accessibility of the sensors. There should be no hesitation in taking a hands-on look at the sensors whenever a performance question arises. Yet this is the most difficult task at most sites. Some sites require special "climbers" to retrieve a sensor and wait to return it to its installed position. These field people may not be trained to handle delicate instruments. It may be so difficult or expensive to get a sensor down that suspected bad data will be accepted rather than facing the problem. This reluctance causes mounting hardware to become corroded to the point that the sensor cannot be removed without damage. Most of the breakage of delicate sensor parts results from handling while climbing on a tower. If the direction sensor does not have an alignment fixture, it may not be possible to remove the sensor without going through the orientation procedure at re-installation.

There are several ways to overcome most of these problems. They all require design forethought in installation. First, the sensors need to be easily removed from the mounting structure. They need to be as easily connected to the rest of the measurement system when they are down, either with the same cable or a suitable substitute cable. One popular cup and vane design uses a crossarm which contains non-removable cabling. Either the whole crossarm assembly must be taken down with the sensors or there has to be a substitute crossarm to plug the sensors into at ground level. Some towers, the short 10 m types, can be tilted to access the sensors while still connected. In this case the sensors are about 90 deg. from their operating position. Some tests require the sensors to be vertical. In these cases the sensor still needs to be removed and re-connected. Ideally, the crossarm is left exactly as is so when the sensor is replaced, nothing physical has changed with respect to verticality or orientation. Some towers telescope for access to the top where wind sensors usually are mounted. This makes access easier but removal and reconnection is still necessary. Some towers have elevators which transport the sensors up and down the tower. How they deal with cables depends on the elevator design.

An ideal installation is one where the operator can get hands on the sensor, perform a test adjacent to the electronics and recorder, and re-install the sensor, safely, alone and within one hour. There are no technological reasons why this cannot be done, except for tall towers where an elevator may take 20 minutes for a one-way trip. There probably is not a budgetary reason for avoiding something like this ideal installation, once the cost of invalid data and true operating costs are factored into the formula. It is usually not done simply because the need for service is overlooked and the method of access is not pre-planned.

4.2.4.2 Wind Speed

The wind speed sensor is most susceptible to error from shadowing and interference. Aside from the need to have the anemometer properly exposed, the only other consideration is verticality (for cup anemometers). If the cup wheel is well balanced, a small angle (1 deg. or less) in mounting is not important. If the cup wheel is not well balanced, the starting threshold will be degraded.

4.2.4.3 Wind Direction

4.2.4.3.1 Exposure

The problem with verticality for the direction vane is just the same as with wind speed. For a well balanced vane assembly, a small angle from vertical is not important. If the vane assembly is not well balanced, the starting threshold is raised and a predominant direction for light winds may not have any basis in fact.

Wind vanes are often used for dispersion applications by calculating the standard deviation of the wind direction about the mean direction, sigma theta. Unless the wind vane is at the tower top, there will be some direction where the wind goes through and around the tower before it gets to the vane. The farther from the tower the wind vane is mounted the smaller the sector with tower interference. The interference sector can be selected by placing the vane on the appropriate side of the tower.

4.2.4.3.2 Orientation

Of all the sources of error for a wind direction measurement, the orientation of the vane to TRUE NORTH has the potential and reputation of being the largest. A bad orientation provides a fixed bias to the data which can be removed. If the vane is moved and the constancy of the bad orientation is in question, the data may not be recoverable. The method of wind vane orientation must be capable of 1 deg. accuracy with 2 or 3 degrees as the upper limit of the error. Two steps are necessary to achieve an oriented wind vane. First, the location of TRUE NORTH must be found to an accuracy of less than 1 deg. Secondly, the wind vane "index" must be aimed at that location with an accuracy of better than 2 deg. (see 4.2.2.2.2.3 for a discussion of the location of the normalized error "index").

TRUE NORTH as distinguished from magnetic north is usually found by reading a magnetic compass and applying the correction for magnetic declination. The declination can be read from a USGS map. The Fox Island Station declination, according to the 1959 (revised in 1981) map, is 20.5°. The USGS is now providing a computer service called GEOMAG. See below:

```
CONNECT
        Unauthorized use of this U.S. Government computer system
                     is punishable under PL98-473
Welcome to the USGS Branch of Global Seismology and Geomagnetism
                On-line Information System
Type Q for Quick Epicenter Determinations (QED)
     H for Historical Epicenter File Searches (EIS)
     M for Geomagnetic Field Values
Enter program option (Q, H or M): m
                                GEOMAG
The International Geomagnetic Reference Field (IGRF) was revised in August,
1987.  The models for 1945.0, 1950.0, 1955.0, and 1960.0 have been superseded
by new definitive models (see, for example, EOS Transactions, American
Geophysical Union, vol. 69, no. 17, April 26, 1988, pages 557-558). The new
models were installed on June 21, 1988.  Please note that the revision affects
field values for dates between 1945.0 and 1965.0, but not those for later
dates.
Problems or suggestions?  Please contact Norman Peddie, U.S. Geological Survey,
MS-968, Federal Center, Box 25046, Denver, CO 80225. Telephone:  (303) 236-1364
(FTS 776-1364).
Press RETURN to continue:
Do you want information about this program (Y/N)?        [ ]  N
Options:   1) Field Values (D, I, H, X, Y, Z, F)
           2) Magnetic Pole Positions
           3) Dipole Axis and Magnitude
           4) Magnetic Center                            [1]  [ ]
Display values twice (Y/N)?                              [Y]  [ ]
   Name of field model:                   [       .]         ?
The following field models are available:
     Name            Type               Date range          Region
    IGRF85     Spherical Harmonic     1945.0 - 1990.0      World
    USCON85    Spherical Harmonic     1985.0 - 1990.0      48-States
    USALA85    Spherical Harmonic     1985.0 - 1990.0      Alaska
    USHAW85    Spherical Harmonic     1985.0 - 1990.0      Hawaii
Name of field model:               [       ]            USCON85
   Date:                           [1/25/89]  [          ]
Latitude:                          [               ]47{.25
North or South (N/S):              [ ]  N.
Longitude:                         [               ]122.6292
East or West (E/W):                [ ]  W
Elevation:                         [0.0]  [250 feet

Model: USCON85    Latitude : 47.25    N
Date : 1/25/89    Longitude: 122.6292 W       Elevation:  250.000 ft

        D            I          H       X        Y       Z        F
   deg  min    deg  min        nT      nT       nT      nT       nT
   19   47.9   69   29.0    19526   18372     6613   52181    55715
   19   47.9   69   29.0    19526   18372     6613   52181    55715
Annual change:
    0   -5.5    0   -0.7     -1.9     8.7    -29.8   -39.6    -37.7
    0   -5.5    0   -0.7     -1.9
```

The GEOMAG program was accessed by calling 1-800-358-2663 through the modem of an "XT clone" using a "ONE TO ONE" communications program. Using the capture feature of ONE TO ONE, the following communication was recorded. Note that the Fox Island Station declination for 1/25/89 is 19.8° or 0.7° less than the map indicated. This is consistent with the 0 deg. -5.5 min. annual change for the roughly eight years since the map was revised.

The other way to find the direction to TRUE NORTH employs some astronomical observation. While the compass method is clearly easiest, it is also the most prone to error. Good training and equipment will reduce these errors to an acceptable level, but not the "less then 1 deg." advised above. Training will minimize errors from the influence of nearby metal objects and the mis-application of the declination correction, but local variation in the isogonic field is unknown. On the other hand, the observation of astronomic bodies can be unambiguous. Polaris, the north star, will provide TRUE NORTH to within 1 deg. (without correction) on any clear night. The true solar noon method will provide the north-south direction to within 0.1 degree on any clear day, given the station longitude, date and an accurate clock. A simple Basic program will provide the azimuth angle to the sun at any time of day given the station longitude, latitude and date. Examples of the two solar methods are given below.

4.2.4.3.2.1 True Solar Noon Method

The True Solar Noon (TSN) method finds the time at some particular date at some particular longitude when the sun is in the north-south plane passing through the North Pole, the South Pole and the longitude selected. If the sun is not directly overhead (elevation 90 deg.) the azimuth line to the sun is TRUE SOUTH or TRUE NORTH. Two calculations are required. First, find the time of the Local Apparent Noon (LAN) from the longitude. The examples shown here are for:

Fox Island, WA (Long. 122.6292, Lat. 47.2500), 07/04/90 and
New Orleans,LA (Long. 90.1100, Lat. 30.0000) 12/25/90.

T_{LAN} = 12:00:00 + 4(Long. - 15n), where n is the number of time zones from Greenwich. Table 4.2.4.1 is a list of n values for United States time zones.

Table 4.2.4.1 Time Zones

Time Zone	n
Eastern	5
Central	6
Mountain	7
Pacific	8
Yukon/Alaska	9
Hawaii	10

T_{LAN}(WA) = 12:00:00 + 4(122.6292 - [15 x 8]) = 12:10.52 = 12:10:31 PST

T_{LAN}(LA) = 12:00:00 + 4(090.1100 - [15 x 6]) = 12:00.44 = 12:00:26 CST

Secondly, correct for the Ephemeris of the sun.

$T_{TSN} = T_{LAN} - A$, where A is the correction found in Table 4.2.4.2.

Table 4.2.4.2 Ephemeris of the Sun

From the Nautical Almanac - 1989 Yachtsman's Edition							
Date	Equation of time m. s.	Date	Equation of time m. s.	Date	Equation of time m. s.	Date	Equation of time m. s.
Jan. 1	-3 24	Apr. 1	-4 00	Jul. 3	-4 05	Oct. 1	+10 11
4	-4 48	4	-3 07	6	-4 37	4	+11 08
7	-6 08	7	-2 16	9	-5 06	7	+12 02
10	-7 24	10	-1 26	12	-5 32	10	+12 52
13	-8 35	13	- 39	15	-5 53	13	+13 38
16	-9 40	16	+ 6	18	-6 09	16	+14 20
19	-10 39	19	+ 48	21	-6 20	19	+14 56
22	-11 31	22	+1 26	24	-6 27	22	+15 27
25	-12 16	25	+1 59	27	-6 28	25	+15 52
28	-12 54	28	+2 29	30	-6 25	28	+16 10
31	-13 25	May 1	+2 53	Aug. 2	-6 15	31	+16 21
Feb. 3	-13 49	4	+3 13	5	-6 01	Nov. 3	+16 25
6	-14 05	7	+3 28	8	-5 40	6	+16 22
9	-14 14	10	+3 38	11	-5 15	9	+16 12
12	-14 16	13	+3 42	14	-4 44	12	+15 54
15	-14 11	16	+3 42	17	-4 08	15	+15 28
18	-14 00	19	+3 37	20	-3 28	18	+14 55
21	-13 42	22	+3 26	23	-2 43	21	+14 14
24	-13 18	25	+3 11	26	-1 55	24	+13 26
27	-12 49	28	+2 52	29	-1 03	27	+12 31
Mar. 2	-12 15	31	+2 28	Sep. 1	- 8	30	+11 29
5	-11 37	Jun. 3	+2 00	4	+ 50	Dec. 3	+10 21
8	-10 55	6	+1 29	7	+1 50	6	+9 08
11	-10 10	9	+ 55	10	+2 52	9	+7 51
14	-9 21	12	+ 19	13	+3 55	12	+6 29
17	-8 31	15	- 19	16	+5 00	15	+5 04
20	-7 38	18	- 58	19	+6 04	18	+3 37
23	-6 44	21	-1 36	22	+7 08	21	+2 08
26	-5 49	24	-2 15	25	+8 11	24	+ 38
29	-4 54	27	-2 53	28	+9 12	27	- 51
		30	-3 30			30	-2 20

T_{TSN}(WA) = 12:10:31 - (-4:16) = 12:14:47 PST = 13:14:47 PDT

T_{TSN}(LA) = 12:00:26 - (-0:08) = 12:00:34 CST

Once the time of TSN is known, all that remains is to observe the position of the line to the sun at TSN. An easy way is to use a loosely mounted theodolite set at 180 deg. to track the sun. **[CAUTION: EYE DAMAGE MAY RESULT FROM LOOKING AT THE SUN WITHOUT SUITABLE PROTECTION** - Remember that harmful UV rays can be present when visual light "looks" safe - **USE AN EYE SAFE FILTER]** When a watch (one second resolution set to WWV or equivalent source for the correct time) shows TSN, tighten the theodolite mounting. At that instant the sun is in the cross hair of the theodolite and the theodolite correctly labels the azimuth angle as 180. Once set, the theodolite can be used to find the bearing to any distant feature which might be selected as an orientation target. Another method is to mark the end of the shadow of a vertical tower at TSN, thus establishing a N-S line from the base of the tower to the mark.

The two drawbacks to the TSN method are weather and schedule. If the sun is obscured at TSN the observation cannot be made. Also, if other activities command higher priorities, the time of TSN might not be available for the sighting.

4.2.4.3.2.2 Solar Azimuth Method

The azimuth angle to the sun can be found at any time if the latitude is also known. A Basic program (Blackadar, 1985) which contains the necessary subroutines has been edited to provide the outputs shown in Figure 4.2.4.1. These are the same two examples as are used in 4.2.4.3.2.1. The program listing is given as Figure 4.2.4.2. Notice in Table 4.2.4.3 that the two methods do not agree. The differences are trivial. Even at the fast angular motion of July, the sun moves about 0.5 deg. per minute. The roughly quarter minute difference in methods represents only a little over 0.1 deg. uncertainty. Notice also the nonlinearity difference between winter and summer which makes simple extrapolation impossible.

A Brunton compass, mounted on a tripod, can be used for solar sighting. The mirror can be set to project the sun and the sighting points and lines on a white piece of paper. The compass needle can be used as a reading index or an additional protractor and pointer can be added to the compass mounting hardware.

```
DAY? 4
MONTH? 7
YEAR? 1990
                    SOLAR AZIMUTH ANGLE
                    WEDNESDAY 4 JUL 1990
              Fox Island, WA
              Longitude 122.6292    Latitude 47.25
              Day of Year 185       Julian Day 2448077
                 Transits Meridian  13  14  53 PDT

         Time              Elevation    Azimuth
HR,MIN? 11,30
                             57.81       130.15
HR,MIN? 12,00
                             61.36       141.90
HR,MIN? 12,30
                             64.00       155.86
HR,MIN? 13,00
                             65.43       171.73
HR,MIN? 13,30
                             65.42       188.40
HR,MIN? 13,00
                             65.42       171.73
```

```
DAY? 25
MONTH? 12
YEAR? 1990
                    SOLAR AZIMUTH ANGLE
                    TUESDAY   25 DEC 1990
              New Orleans, LA
              Longitude 90.11       Latitude 30
              Day of Year 359       Julian Day 2448251
                 Transits Meridian  12  0  34 CST

         Time              Elevation    Azimuth
HR,MIN? 10.30
                             32.35       155.29
HR,MIN? 11.00
                             34.67       163.07
HR,MIN? 11:30
                             36.11       171.33
HR,MIN? 12.00
                             36.61       179.86
HR,MIN? 12,30
                             36.14       188.38
HR,MIN? 13,00
                             34.73       196.65
```

Figure 4.2.4.1 *Screen printouts for two azimuth examples*

Table 4.2.4.3 Solar Method Comparisons

Lo,La,D	WA (7/4/90)			LA (12/25/90)		
Method	TSN	Almanac	dif.	TSN	Almanac	dif.
Units	PDT	PDT	(s)	CST	CST	(s)
TSN	13:14:47	13:14:53	-6	12:00:34	12:00:34	0

where Lo is the station longitude
La is the station latitude
D is the date of interest

```
50 STA$="MSI, Fox Island, WA":REM STATION NAME
60 READ LO,LA
100 DATA 122.629,47.25:REM LONGITUDE & LATITUDE
110 READ PI,OB,L0,L1,A0,A1,EC,EO
120 DATA 3.141592654,.409095,4.88376619,.017202791
130 DATA 6.23471229,.017201970,.016728,.00218
140 TR=PI/180:FC=2*PI:REM TO RADIANS; FULL CIRCLE
150 SL=15*INT(LO/15+.5):REM STANDARD LONGITUDE
180 TZ=SL/15-4: REM SELECTS TIME ZONE LABEL
190 LO=LO*TR:LA=LA*TR:SL=SL*TR
210 D1$="SUNDAY   MONDAY   TUESDAY  WEDNESDAY"
220 D2$="THURSDAY FRIDAY   SATURDAY"
230 D$=D1$+D2$ : X$=" ** "
240 M$="JANFEBMARAPRMAYJUNJULAUGSEPOCTNOVDEC"
250 Z$="ASTESTCSTMSTPSTYSTASTADTEDTCDTMDTPDTYDTADT"
260 TN=LO/FC+.5:REM LONGITUDE TIME OFFSET + 12 HR
270 PRINT "DAY";:INPUT D
280 PRINT "MONTH";:INPUT M
290 IF M>12 THEN PRINT "INVALID DATE":GOTO 280
300 PRINT "YEAR";:INPUT YR
310 X=1:Y=1:GOSUB 2410
320 J1=T:REM YEAR DAY 1
330 X=D:Y=M:GOSUB 2410
340 YD=T-J1+1:REM DAY OF YEAR
350 X=INT(T+1)/7:Y=INT(X)
360 WD=INT(7*(X-Y)+.5):REM DAY OF WEEK
380 T=T+3449.5+TN:REM T IS NOW TIME OF LOCAL MEAN NOON
385 DT=.00059+2.2E-08*T : T=T+DT : REM EPHEMERIS TIME
390 PRINT TAB(28);"SOLAR AZIMUTH ANGLE"
405 PRINT TAB(29);
410 PRINT MID$(D$,9*WD+1,9);
420 PRINT D;MID$(M$,3*(M-1)+1,3);YR
423 PRINT TAB(20);STA$;
426 PRINT TAB(20);"Longitude";LO/TR;TAB(42);"Latitude";LA/TR
430 PRINT TAB(20);"Day of Year";YD;TAB(42);"Julian Day";INT(JD+1)
490 X=YD-WD: Y=SL-15*TR
500 IF X>90 AND X<298 THEN TZ=TZ+7 : SL=Y
510 T$=MID$(Z$,3*TZ+1,3)
610 GOSUB 2860: REM FIND SUN AT LOCAL MEAN NOON
620 IF DE>PI THEN DE=DE-FC
630 Q=ML-RA:REM EQUATION OF TIME (NOT DISPLAYED)
640 D3=DE : REM SAVE DECL FOR HEAT BUDGET
680 X=-.0145439 : GOSUB 2360
690 IF ABS(Y)<1 THEN 720
710 GOTO 780
720 S0=Z*(1+L1/FC) : H=-S0 : GOSUB 2260
725 TC=.00274*S0*SIN(OB)*COS(TL)*SIN(LA)
730 Z=SIN(S0)*COS(LA)*(COS(DE)^3)
735 TC=TC/Z
740 X=ZT+TC+EO : GOSUB 2310
780 PRINT TAB(23);"Transits Meridian ";
790 IF ABS(LA-DE)>PI/2 THEN PRINT X$;X$;T$
800 H=0 : GOSUB 2260
810 X=ZT : GOSUB 2310
820 PRINT X;Y;Z;T$
830 PRINT
850 PRINT TAB(12);"Time          Elevation   Azimuth"
1990 GOTO 4000
2010 C=0:N=0
2020 IF Y<>0 THEN 2050
2030 Z=0:C=1:IF X<0 THEN N=1
2040 GOTO 2060
2050 Z=X/Y
2060 Z=ATN(Z)
2070 IF C=1 THEN Z=PI/2-Z
2080 IF N=1 THEN Z=-Z
2090 IF Y<0 THEN Z=Z+PI
2100 IF Z<0 THEN Z=Z+FC
2110 RETURN
2160 CZ=SIN(LA)*SIN(DE)+COS(LA)*COS(DE)*COS(H)
2165 SZ=SQR(1-CZ^2): ZA=ATN(SZ/CZ)
2170 IF ZA<0 THEN ZA=ZA+PI
2175 X=COS(DE)*SIN(H)/SZ
2180 Y=(SIN(LA)*CZ-SIN(DE))/(SZ*COS(LA))
2185 GOSUB 2010
2190 AZ=Z : IF AZ>PI THEN AZ=AZ-FC
2195 RETURN
2210 H=ZT+SL-RA-LO+ML+PI
2220 IF H>PI THEN H=H-FC
2230 RETURN
2260 FOR IJ=1 TO 5
2265 ZT=H+RA+LO-SL-ML-PI
2270 X=SIN(ZT) : Y=COS(ZT) : GOSUB 2010
2275 ML=L0+L1*(T-TN+(SL+Z)/FC) : NEXT IJ
2290 ZT=Z : RETURN
2310 IF X<0 THEN X=X+FC : GOTO 2310
2315 W=X*24/FC : X=INT(W)
2320 Z=(W-X)*60 : Y=INT(Z)
2330 Z=INT((Z-Y)*60) : RETURN
2360 Y=(X-SIN(LA)*SIN(DE))/(COS(LA)*COS(DE))
2370 IF ABS(Y)>1 THEN 2390
2380 X=SQR(1-Y^2) : GOSUB 2010
2390 RETURN
2410 T=367*(YR-1980)
2420 T=T-INT(7*(YR+INT((Y+9)/12))/4)
2430 S=SGN(Y-9):A=ABS(Y-9)
2440 Z=INT((YR+S*INT(A/7))/100)
2450 T=T-INT(3*(Z+1)/4)
2460 T=T+INT(275*Y/9)+X-.5
2470 JD=T+2447689#
2480 RETURN
2860 MA=A0+A1*T: REM SUN'S MEAN ANOMALY
2870 ML=L0+L1*T: REM SUN'S MEAN CELESTIAL LONGITUDE
2880 X=SIN(ML):Y=COS(ML):GOSUB 2010
2890 ML=Z
2900 DL=2*EC*SIN(MA)+1.25*EC^2*SIN(2*MA)
2910 TA=MA+DL:TL=ML+DL:REM TRUE ANOMALY & LONGITUDE
2920 RV=(1-EC^2)/(1+EC*COS(TA)):REM RADIUS VECTOR
2930 X=SIN(TL)*SIN(OB):Y=SQR(1-X^2):GOSUB 2010
2940 DE=Z:IF Z>PI THEN Z=Z-FC
2950 X=SIN(TL)*COS(OB):Y=COS(TL):GOSUB 2010
2960 RA=Z:REM SUN'S RIGHT ASCENSION
2970 RETURN
4000 INPUT "HR,MIN";HR,MIN:
4010 ZTH=HR+MIN/60 : ZT=ZTH*FC/24
4020 T=T-TN+(ZT+SL)/FC
4060 GOSUB 2860
4070 GOSUB 2210
4080 GOSUB 2160
4090 AL=PI/2-ZA
4110 PRINT TAB (24);
4113 PRINT USING "     ####.##";AL/TR,180+(AZ/TR)
4117 GOTO 4000
9000 END
```

Figure 4.2.4.2 *Basic program listing for finding solar azimuth as a function of Longitude, Latitude, Date and Time*

4.2.5 CALIBRATION

Calibration, as defined on page 3 of the Purpose statement in the beginning of this handbook, qualifies the process as both a measurement and adjustment, if necessary, of the performance of the system and its components. Manufacturers usually include in their manuals the details of all the available calibration or adjustment points. From a QA standpoint, the important consideration is how the system is working as a whole. Since only parts of the system are adjustable, the relationship of these adjustments to the whole system must be known. This brief section will focus on documentation of calibrations and methods to verify the system response to subcomponent adjustments.

4.2.5.1 Wind Speed

4.2.5.1.1 System accuracy

The part of a calibration which challenges the entire system, except for the coupling or reaction of the sensor to the wind,relates the rate of rotation of the anemometer shaft to output speed. It does not matter if the rate of rotation is caused by a synchronous motor or a d.c. motor with a provision for shaft revolution counting. What does matter is the accuracy of the determination of AVERAGE rate of rotation and a common averaging PERIOD used by the system and the challenge. The operators may choose to conduct this calibration with the sensor installed on the tower. When multiple outputs exist, the calibration should record values from each of them, but the critical output is the one used to produce the official archieved data.

The accuracy determination depends on both the method used in the challenge and the accuracy of the measurement of the input. If a synchronous motor is used, there must be some reason to believe the motor was turning in sync with the commercial power. Repeated samples which do not change is one form of evidence. Commercial power is generated within a frequency tolerance of 60 ± 0.1 cps. Synchronous motors which are hand held with a flexible coupling to the anemometer shaft may go in and out of sync providing a slightly changing output. Shaft rotation counters can also produce erroneous outputs. Some evidence of their performance, such as counting a synchronous motor shaft rotation or simply counting revolutions at a slow rate, is needed in the documentation of the test equipment, preferably before and after field use.

4.2.5.1.2 Component accuracy

If the system has built in calibration circuits, they should be calibrated at the same time as the total system. They are handy to use on a routine service schedule, but there needs to be some evidence of their calibration. If panel meters or portable DVOMs are used to check the signal conditioner or transducer sub-system, there needs to be evidence that they are in calibration. It is possible to adjust a circuit to provide the required output on a meter which has a 2% error and thereby introduce a 2% error to the calibrated system output.

The calibration of the sensor starting threshold can only be a measurement. Adjustment is usually impossible. The exception might be the amount of end play in the shaft-bearing assembly, but that level of sensor repair is usually left to the laboratory or shop for good reason. The accuracy of the torque measurement, or non-measurement, is also important. Assume a torque watch, or similar device, with a range of 0.003 to 0.030 oz-in. The threshold of measurement is 0.003 oz-in or 0.22 g-cm. If a cup anemometer has a K value of 1.4 (see 2.1.1.2), the torque provided by a 0.4 m/s (0.9 mph) wind is 0.22 g-cm [from $T=Ku^2$]. The torque provided by a 0.5 m/s (1.1 mph) wind is 0.35 g-cm. If the torque watch cannot measure the starting torque of the shaft because it turns before the indicator moves, the starting torque is < 0.22 g-cm and the starting speed is < 0.4 m/s. If, instead, the starting torque reads 0.35 g-cm (0.005 oz-in), the starting speed is 0.5 m/s and within specification. If the starting torque reads 1.0 g-cm (0.014 oz-in or about half scale on the torque watch), the starting speed is 1.4 m/s and clearly in need of service. Documentation of this measurement will tell the data QC inspector that the data from this anemometer is in error in the indicated 0.2 (assuming a 0.2 m/s offset) to about 3 m/s range. (3 m/s wind provides 12.6 g-cm torque or about an order of magnitude more than that provided at 1 m/s. The difference between 0.35 and 1.4 is not likely to be visible at 12.6) The true wind speed will be higher than the indicated speed. At indicated 0.3 m/s it would be 1.5 m/s and at indicated 3 m/s it would really be 3 m/s.

4.2.5.2 Wind Direction

4.2.5.2.1 System accuracy

The system calibration of a wind vane can be checked on the tower by aiming the vane to and from known directions, such as a distant mountain peak or similar feature. If checks are made with respect to a mounted component, such as a crossarm, the orientation of the crossarm also needs to be checked. A single distant feature should be the orientation target with a known bearing with respect to TRUE NORTH. Other targets can be secondary checks which challenge both the orientation and the performance of the transducer. For systems using the 540 format, the targets should be reached after a clockwise revolution and then again after a counter clockwise revolution to challenge both parts of the transducer.

Before the transducer is removed from the tower, a documentation of the as-found output with the vane held pointing at or from the orientation target is essential. This single act provides the basis for data validity for the period beginning with the previous as-left record and ending with this as-found reading. Since the sensor should not have been removed from the tower or adjusted in orientation without the as-found and as-left readings, these values should be the same, within the capability of pointing the vane (1 deg., 2 deg. at the most). If they are not, the data QC inspector will have some detective work to do. Usually, when the sensor is removed and used in a calibration at the location of the rest of the system, replacement in a keyed fixture will cause the as-left value to be the same as the as-found. Figure 4.2.5.1 shows three examples of how manufacturers provide an orientation key for wind direction sensors. If there is no keyed fixture, the full orientation procedure will be required.

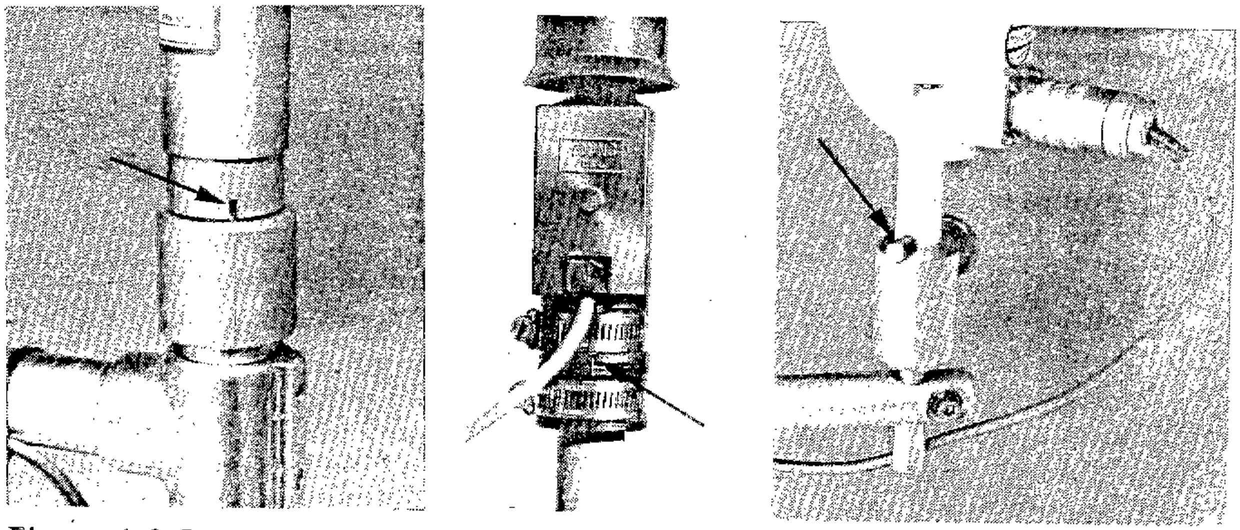

Figure 4.2.5.1 *Methods for keying orientation of direction sensors*

One simple orientation procedure requires a clamp which will hold the vane from turning. A hose clamp will work for some designs. Figure 4.2.5.2 shows a hose clamp used for this purpose. Tape which does not stretch is marginally useful. Stretchy tape like duct tape or electricians tape will only work on a perfectly calm day. Set the vane so that the output is the correct value for the orientation target (see 4.2.2.2.2.1). If the angle of the orientation target is coincident with a +2 deg. error relative to the average error of 0 deg., the output should be 2 deg. higher than the bearing of the orientation target. Only in this way will the relative error of the sensor be distributed equally about TRUE directions. Tighten the clamp so the output is both correct and constant. Mount the clamped sensor on the tower and turn it until the vane points at the orientation target. Clamp the vane in place. Verify that the output is still correct before removing the vane clamp.

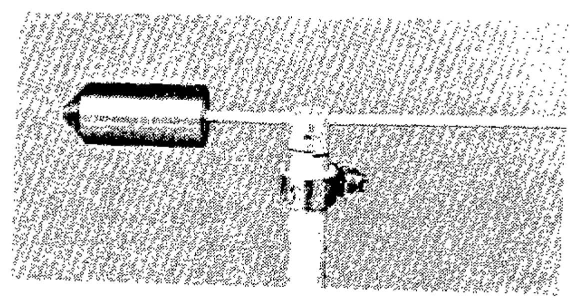

Figure 4.2.5.2
A direction vane clamp

4.2.5.2.2 Component accuracy

The same comments regarding calibration circuits, parallel recorders and panel meters apply to wind direction as they do to wind speed, mentioned in 4.2.5.1.2 above. With the sensor next to the signal conditioner (attached with either the operating cable or a suitable substitute) and with a fixture which holds known relative directions, the signal conditioner can be adjusted if required. The 540 offset voltage, if one is used, can be tested and adjusted. The output voltage vs. position can be set. The open space in the potentiometer, if one is used, can be measured and adjusted for.

A single potentiometer has an electrical range of something like 355 deg. with a mechanical range of 360 deg. If the transfer function of relative direction to voltage output is

$$\theta = 360 \times V$$

where θ is the angle in deg. and V is the output in volts (0-1 V scale), and the maximum "full scale" output, set by shorting the potentiometer wiper to the high side of the potentiometer, is 1.000 V, a small error will have been set into the system. The error will be +1.4 % of reading. At 355 deg. the output will be 360. At 180 deg. the output will be 182.5 deg. This adjustment error added to the linearity error of the potentiometer may be more than is acceptable. If instead, the signal conditioner is set to output 0.986 V when the vane is set to 355 deg., the output will be 355 deg. (360 x 0.986). At 180 deg. the output will be 180 (assuming no linearity error). All of the error between 355 deg. and 360 deg. is in that 5 deg. sector.

Is this acceptable for PSD (EPA, 1987a) applications? The "wind direction system error" which cannot exceed 5 deg. is the error of the averaged wind direction samples. If the mean direction were 355 deg. with a range of ±5 deg., and if the distribution were bi-modal with half the values at 350 deg. and half at 360 deg., and if the output voltage remained at 0.986 V between 355 deg. and 360 deg., the average output would be 352.5 deg., a -2.5 deg. error. If the dead space were at 0 V, the output would cause the bi-modal distribution to look like half 350 deg. and half 360 deg. producing the correct average of 355 deg. This is a maximum error estimate. True distributions would cause smaller average errors. Even a wind averaging 357.5 deg. with a range of ±2.5 deg (the vane is always in the dead space), the error is 2.5 deg.

The starting threshold of the wind vane is important to accurate low wind speed directions. The design of the vane along with the off-set angle (or error tolerance) provides a K value. The K value along with the starting torque of the vane assembly provides a threshold wind speed. Assume a 5 deg. error tolerance and a K value of 15. At 0.5 m/s the available torque is 3.75 g-cm. At 10 cm out from the axis or rotation, a force of 1/3 of a gram should move the vane assembly. This is another threshold of the torque gauge situation. At 1 m/s the torque available is 15 g-cm and at 10 cm the force is a reasonable 1.5 g. At 1 m/s and 10 deg. error tolerance, K becomes 37.5, the torque available becomes 37.5 g-cm, and the force at 10 cm is an easily measured 3.75 g.

4.2.6 OPERATIONS, MAINTENANCE AND QUALITY CONTROL

4.2.6.1 Operations

The important aspects of operations, from the standpoint of quality assurance, are planning (see QA Plan, Section No. 4.1.) and documentation (Section No. 4.9.1). The purpose of operations is to acquire valid data. For wind measurements, this requires frequent (weekly, if possible) visual examination of the sensors. This is not a "hands-on" examination but simply a look at the active shapes, cups, propellers and vanes, to be sure there has been no physical damage. Sensitive wind instruments can be damaged by hail and by birds. The nature of an analog recording, if one is used routinely, will tell how the sensor is performing. Routine entries in the station log will provide the evidence of attention to support validity claims.

Calibrations are a part of operations. A member of the operating organization needs to become the "expert" on how the measurement system works and what it needs to continue "in control" performance. Regularly scheduled calibrations build the expertise and the documentation showing measurement accuracy. The frequency of calibrations is a variable. For a new installation, a calibration during the installation is necessary. A careful look at the first week of operation will find early failures. If all seems to be going well, a calibration check after a month is prudent. If no problems surface, a full calibration at the end of the first quarter is advisable. For some site environments and some applications quarterly calibrations are recommended. Semi-annual calibration is the minimum frequency. If problems are found they must be documented and corrected as quickly as possible. The requirement of 90% joint frequency of valid wind and stability data does not permit much down time. The frequency of calibrations or calibration checks should be determined by the performance of the instrument system. If problems occur, the week-month-quarter frequency should begin again. When it is demonstrated that the system is once again "in control," routine calibration frequency (semi-annual or quarterly) can resume.

4.2.6.2 Maintenance

4.2.6.2.1 Routine and preventive maintenance

The only routine maintenance required for the wind system should be applied during routine calibrations. Sensors exposed to the elements need cleaning and protective lubricants applied to their mounting hardware. When a sensor needs to be removed for close inspection or calibration and it cannot easily be removed because set screws or nuts are locked to their threads by corrosion, a failure in routine maintenance is the reason.

If the system has supply requirements, such as ink and paper for analog recorders or tapes and printer paper for digital recorders, the timely servicing of these requirements is a routine maintenance task.

Preventive maintenance must at minimum follow the manufacturer's recommendations. Considerable damage can result by ignoring this guidance. Some people like to oil anything that moves. Sensitive wind sensors require specific care if the threshold is to be maintained.