4.2.6.2.2 Corrective maintenance

Parts for wind systems are not to be found anywhere except from the manufacturer. This is true at least at the sub-component and component level. When a part fails or wears out, the new part usually must come from the manufacturer. This may take a week or two depending on the part and the manufacturer. It is prudent to have spare parts on hand to cover some predictable failures. A component plug-in philosophy is the quickest way to correct failures. If a bearing or a potentiometer fails in a sensor, a new calibrated sensor is simply plugged in while the failed one is repaired. If a circuit card fails, a new calibrated card is plugged in while the failed one is repaired.

The next level of spare part strategy is the sub-component level. Critical and difficult to buy parts are stocked and used to repair sensors or circuit cards. Conventional sensors will always need repair at some point in time, bearings and direction potentiometers usually. Circuit cards are becoming so reliable that maintenance is hard to anticipate.

4.2.6.3 Quality Control

The quality control (QC) of a data monitoring program is a loop driven by routine inspection of the data for validity. The data QC person should be a meteorologist who is familiar with how wind data should look and what kinds of variety are provided by the atmosphere. Such an inspector will spot problems before they are obvious to an observer who may be an expert in another field but is not a meteorologist. If a technically qualified QC inspector is not available, the best compromise that is available must be made. It is very dangerous in terms of lost time if no routine data QC function is followed in the QA Plan, or if there is no QA Plan.

When a problem is found by the data QC inspector, a discrepancy report is issued which brings the operators into the data QC loop. Their inspection and corrective action is reported back to the QC inspector closing the loop. Because of this QC loop, the measurement system can be operated "in control" and valid data produced.

4.2.7 PERFORMANCE AUDIT METHODS

4.2.7.1 General Considerations

A performance audit is the determination of the instrument system accuracy made with an independently selected method and by a person who is independent of the operating organization. To make this determination for wind measurements, knowledge of the input conditions imposed upon the sensors is required. Given knowledge of these input conditions, the transfer functions and the system's data handling method, the output can be predicted. The difference between the predicted output and the system output is the error of the system or its accuracy.

The methodology starts with the ways of controlling and/or measuring the input conditions. When controlled inputs are used, as should always be the case for starting thresholds, anemometer rate of rotation vs. output and relative vane position vs. output, the accuracy of the output is easily determined. Of course, the accuracy of the anemometer transfer function is not a part of this determination. When the input conditions are not controlled, as with the collocated transfer standard (CTS) method, the accuracy determination has a larger uncertainty. The CTS method does challenge the anemometer transfer function. The best performance audit uses both methods where appropriate.

A performance audit must follow some written procedures. Since the procedures must be relevant to the design of the instrument or system being audited, only general principles will be described below with some specific examples. The data from the audit should essentially fill out an audit form. It is important, however, for the auditor to be sufficiently experienced to be able to deviate from the procedure or the form when the pursuit of truth leads away from the expected.

The starting point of an audit form is the documentation of the who, what, where, when, and how the audit values were acquired.

4.2.7.1.1 Who

The performance audit report form should contain a space to identify the auditor. The audit report which summarizes the audit findings should report the names and affiliations of the operators of the system.

4.2.7.1.2 What

The form should contain a section to identify the instrument being audited by manufacturer, model number, and serial number. Sub-assemblies, such as a cup wheel of an anemometer, should be identified by number. If they are not numbered, the operator should be asked to mark them for identification.

The audit report should contain a list of all the equipment provided and used by the auditor, including model and serial numbers and time of last calibration, where relevant.

4.2.7.1.3 Where

The audit form should have a space to show the location of the sensor on a tower, including height. A sketch is useful to show the relative positions of the sensing elements with respect to possible biasing influences, such as the tower, other sensors and buildings.

4.2.7.1.4 When

The date or dates when the audit affected the system operation should be listed. The time when the system or a particular sensor was taken "off-line" and put back "on-line" should be listed. The time, or time period, when each datum value was taken is vital for the comparison with the system output. Implicit in this is the need for the time the auditor uses to be correlated to the time the operator or the system uses. The auditor should rely on the National Bureau of Standards station WWV for correct time. Battery operated receivers, such as the Radio Shack Time Cube, are generally available.

4.2.7.1.5 How

The audit form should either contain a copy of the method used or reference the method number. The audit report should contain copies of the audit method used. The methods should be detailed enough to identify each step in the acquisition of the audit value and in the conversion of the value to units compatible with the system output.

4.2.7.2 Wind Speed

There are two general philosophies in use by those who operate anemometers in meteorological monitoring systems and networks. The most common treats the system as a unit where the sensor and signal conditioner and recorder are calibrated together. The other, often employed by operators with large numbers of anemometers, considers the sensor as a standard interchangeable part. In this case two audits are necessary. One to challenge the sensor calibration method and the other to challenge the system calibration using a standard signal as a substitute for the sensor. A full system audit method from sensor input to system output can be used as a challenge for the system operated with interchangeable sensors.

4.2.7.2.1 Sensor Control

The controlled condition is rate of rotation of the anemometer shaft. The cup assembly or propeller is removed for this challenge. The audit form should provide space for fully defining the transfer function used by the operators (usually supplied by the manufacturer). This should include the relationship of rate of rotation (R, rps) to wind speed (U, m/s), rate of rotation to output volts (O, V) and rate of rotation to frequency (f, Hz), for light chopper or a.c. generator types. See 4.2.2.1.2 for a discussion of the U=a+bR and U=bR types of transfer functions and how the constants "a" and "b" are determined. Some manufacturers provide the transfer function in the form

$$f = 26.439\ (U - 0.281)$$

which can be converted to

$$U = 0.281 + 1.135R$$

once the number of pulses per revolution (30 in this case) is known.

The rate of rotation can be imposed on the anemometer shaft in a number of ways. If the method is to drive the shaft with a d.c. motor, the number of revolutions of the shaft over a period of time is the data value. That value divided by the number of seconds in the time period gives average rate of rotation R (rps). The R is converted to U by the transfer function and the U is compared to the system output in the same units for exactly the same period of time. If the system provides 5 minute average speeds, the count is for 5 minutes with the start and stop times inclusive of the system period. If the d.c. motor is reasonably constant (± 10%), a few seconds out of synchronization over 300 seconds is acceptable. The period of time, however, must be exactly 300 seconds which can be hand timed with a sweep second watch to about ± 0.2 s. If the system only reports hourly averages, and cannot be changed to a shorter time, samples of the signal conditioner output voltage may be used to estimate the system output. Three rates of rotation in addition to zero are recommended. Since the important speeds are low speeds and not full scale speeds, the use of simulated speeds on the order of 2, 5 and 10 m/s is acceptable. Using the transfer function above, these speeds are simulated by R values of 1.51, 4.16 and 8.56 rps (90.6, 249.6 and 513.6 rpm). Figure 4.2.7.1 is an experimental d.c. motor drive used for this kind of audit. Figure 4.2.7.2 is a second generation d.c. motor drive capable of being powered by a D cell and a 9 volt transistor battery.

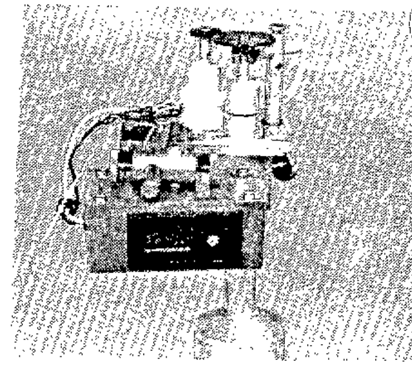


Figure 4.2.7.1

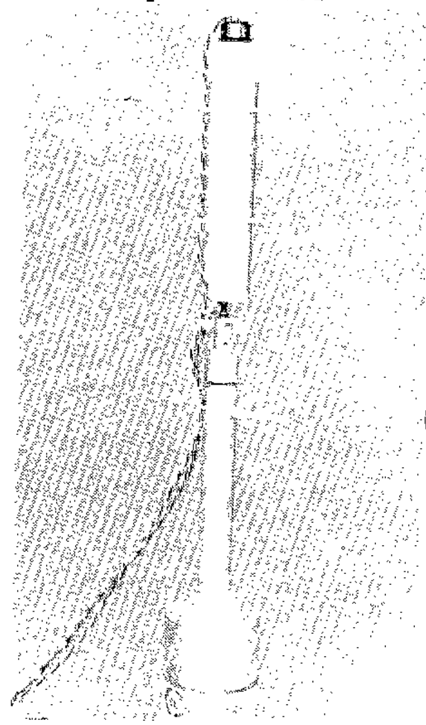


Figure 4.2.7.2

If a propeller anemometer with a transfer function of

$$U = 0.294R$$

is challenged, the speeds of 2, 5 and 10 m/s will be simulated by 6.9, 17, and 34 rps (414, 1020,and 2040 rpm). If the auditor could generate five R values, 1.5, 4, 7, 17 and 35 rps, both cups and propellers could be challenged at three meaningful speeds plus zero. See Figure 4.2.7.3 for a third d.c. motor system.

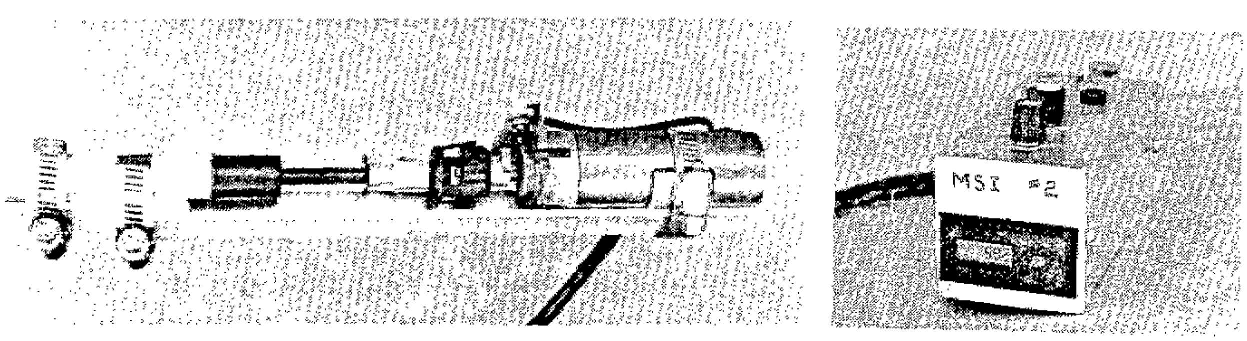
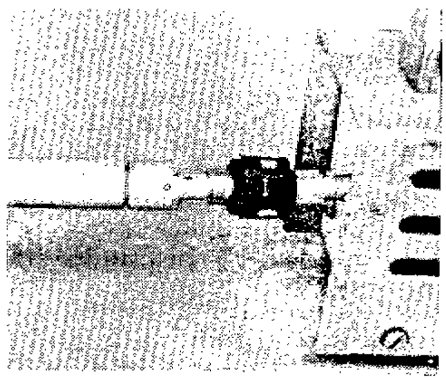
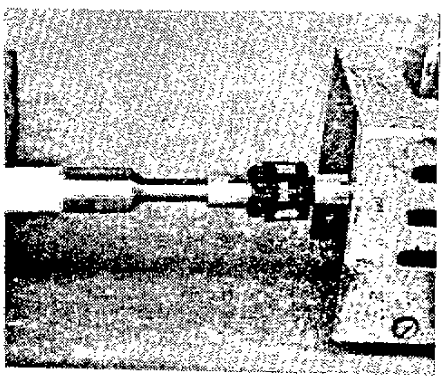


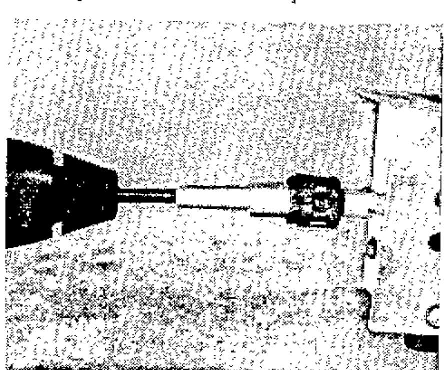
Figure 4.2.7.3 *An experimental 12-volt d.c. motor and counter*



Climatronics cup



Teledyne-Geotech cup



R.M. Young propeller

Figure 4.2.7.4

A simple d.c. motor might be made to turn the shaft, but the key to the audit challenge is the measurement of the shaft revolutions. A light chopper and counter is a straight forward approach to this measurement. Hand switching the counter for periods as short as 60 s will produce better than one percent accuracy in time. If the light chopper produced 10 counts per revolution, the count rate required for the four R values mentioned above is 5 to 60 Hz, an easy range for simple battery operated counters. A system such as described above has the advantage of independence from commercial power, a significant advantage for some remote wind systems.

The controlled condition audit requires a hands-on policy regarding the sensor. The measurements of the starting torque does not require the sensor to be connected to the circuit. It is possible, with proper equipment and care, to install the speed challenge motor on the sensor and operate that challenge with it connected in its operating location. Another way to challenge an anemometer is to connect the shaft to a synchronous motor. The assumption here is that the motor is running in synchronization and the R value is therefore known from the specifications of the motor or an independent measurement of its rate of rotation. Figure 4.2.7.4 shows three anemometers coupled to a synchronous motor through a universal coupler.

The last measurement is the time constant. With the simulated speed on its highest rate, and with a meter on the output voltage of the signal conditioner, turn off the d.c.motor and measure the time it takes to reach the value of the simulated speed minus 63% of the simulated speed. Examples of wind speed audit procedures and forms are found in Figures 4.2.7.5 through 4.2.7.8.

Cup Anemometer - MSI method CA003 (version 8/1/84)

This method provides for a comparison of the transfer function used with the system to the output of the system. This is done by causing the anemometer shaft to turn at a known rate of rotation and observing the output. The means of turning the shaft and measuring the rate of rotation are provided by the auditor and are completely independent of the operating system. The method does not challenge the transfer function. This can be done best with a wind tunnel test.

The report form for this method includes space for an optional determination of starting torque and system time constant. The torque measurement may be used as an indication of bearing condition and hence starting threshold of the anemometer. The time constant is of use if turbulence is measured.

CA003-A Remove the cup assembly. Mount a coupler to the anemometer shaft. A 1/8" shaft is required. If the anemometer does not use that size or it is not accessible, an interface fitting will be required. Clamp the drive motor to the support column of the shaft so that the coupler is engaged with the drive wheel. Determine if the cup assembly turns the shaft in a clockwise or counter clockwise direction, when viewed from above. Clockwise is common and is used on the form. Operate the drive motor at two speeds (find the desired rps from the transfer function) which are important to the application of the wind speed data. Use a time period synchronous with the system output. An average of one minute or longer is required. If the system provides only instantaneous samples of output volts, take 12 samples over a two minute period and use the average of the samples to compare with the average rate of rotation measured.

CA003-B This method requires that the system be operating with all cables in place (short jumper cables may be used with CA003-A to allow simultaneous access to the anemometer and the signal conditioner for those systems where these two parts are at some distance away). At least a zero rate of rotation must be measured (or observed) with the anemometer in place, the cup assembly removed and the shaft taped to assure non-rotation. A second observation may be either a motor driven measured rate of rotation for the operating period of the system or a natural (unmeasured) non-zero operation to assure that signal reaches the signal conditioner when the system is in operating position. The assumption with the later choice is that if the signal is transmitted at all it will be properly simulated in method A. This is more likely true with pulse trains than with generator voltages.

Figure 4.2.7.5 *Audit method for a cup anemometer*

PERFORMANCE AUDIT REPORT by ______________ CA003

MEASUREMENT SYSTEM - Cup anemometer
System number ________________________________
Sensor ________________________________
Cup assembly ________________________________
Location ________________________________
Signal conditioner ____________________________
Data channel ________________________________

DATE __/__/__ TIME off line ______ on line ______ test start ____

TRANSFER FUNCTION: (rps to mps) ______________________________
(rps to volts) ____________________________
pulses per revolution ________

TEST RESULTS

CA003-A

	- challenge speed -				output	difference	
	time	revs.	rps	mps	mps	mps	%
0	______	0	0	______	______	______	______
"d.c."							
S CW	______	______	______	______	______	______	______
F CW	______	______	______	______	______	______	______

Torque: _______ Oz.-In. cw, Time constant _____seconds

CA003-B

	time	expected mps	observed mps	difference mps	%
0	______	______	______	______	______
test	______	______	______	______	______

Figure 4.2.7.6 *Audit form for the cup anemometer method*

Fixed Axis Propeller - MSI method FAP001 (version 8/1/84)

This method provides for a comparison of the transfer function used with the system to the output of the system. A seperate form is provided for W (vertical component) since a different transfer function is often used for this direction than is used for U and V. The method causes the propeller shaft to turn at a known rate of rotation while observing the output. The means of turning the shaft and measuring the rate of rotation are provided by the auditor and are completely independent of the operating system. The method does not challenge the transfer function. This can be done best with a wind tunnel test. The sign convention used with respect to clockwise and counter clockwise is that of the system being challanged. Differences are always calculated by subtracting the audit challange value from the system output. Arithmetic convention is followed even though the minus sign is used as an indicator of direction. For example, the difference between a -1.5 mps audit challenge and a -1.3 mps system output is +0.2 mps even though the system underestimated the speed (a negative error) with respect to the audit value in the "-" direction.

The report form for this method includes space for an optional determination of starting torque and system time constant. The torque measurement may be used as an indication of bearing condition and hence starting threshold of the propeller. The time constant is of use if turbulence is measured.

FAP001-A Remove the propeller. Mount a coupler to the propeller shaft. A 1/8" shaft is required. If the propeller does not use that size or it is not accessable, an interface fitting will be required. Clamp the drive motor to the support column of the shaft so that the coupler is engaged with the drive wheel. Operate the drive motor in both a clockwise and counter clockwise direction, when viewed from in front of the propeller. Operate the drive motor at two speeds (find the desired rps from the transfer function) which are important to the application of the wind speed data. Use a time period synchronous with the system output. An average of one minute or longer is required. If the system provides only instantaneous samples of output volts, take 12 samples over a two minute period and use the average of the samples to compare with the average rate of rotation measured. If a synchronous motor is used as the drive motor, an instantaneous sample voltage may be used. Some evidence of the synchronous operation of the motor is required.

CA003-B This method requires that the system be operating with all cables in place (short jumper cables may be used with FAP001-A to allow simultaneous access to the propeller and the signal conditioner for those systems where these two parts are at some distance away). At least a zero rate of rotation must be measured (or observed) with the propeller shaft in place. the propeller removed and the shaft taped to assure non-rotation. A second observation may be either a motor driven measured rate of rotation for the operating period of the system or a natural (unmeasured) non-zero operation to assure that signal reaches the signal conditioner when the system is in operating position.

Figure 4.2.7.7 *Audit method for a propeller anemometer*

PERFORMANCE AUDIT REPORT by ______________ FAP001W

MEASUREMENT SYSTEM - Fixed axis propeller

System number ______________________________
Sensor ______________________________
Propeller ______________________________
Location ______________________________
Signal conditioner ______________________________
Data channel ______________________________

DATE __/__/__ TIME off line _____ on line _____ test start ____

TRANSFER FUNCTION: 1 rps = 0.294 mps (3 pulses per revolution)
[W(volts)-2.5]*4 = m/s

TEST RESULTS

FAP001W-A	- challenge speed -				output	difference	
	time	revs.	rps	mps	mps	mps	%
0	_____			0	_____	_____	_____
"d.c."							
S CW	_____	_____	_____	_____	_____	_____	_____
S CCW	_____	_____	_____	_____	_____	_____	_____
F CW	_____	_____	_____	_____	_____	_____	_____
F CCW	_____	_____	_____	_____	_____	_____	_____
"sync"	time	rps	mps	volt	mps	mps	%
S CW	_____	5.000	1.47	_____	_____	_____	_____
S CCW	_____	5.000	-1.47	_____	_____	_____	_____
F CW	_____	30.00	8.82	_____	_____	_____	_____
F CCW	_____	30.00	-8.82	_____	_____	_____	_____

Torque: _____Oz.-In. cw, _____Oz.-In. ccw, T. Const._____s.

FAP001W-B	time	expected mps	observed mps	difference mps	%
0	_____	_____	_____	_____	_____
test	_____	_____	_____	_____	_____

Figure 4.2.7.8 *Audit form for the propeller anemometer method*

4.2.7.2.2 CTS Method

The collocated transfer standard (CTS) method for wind speed involves mounting a carefully calibrated anemometer in the vicinity of the subject anemometer being audited. The CTS should have certificates tracing its calibration to NBS or some other standard facility. If the ASTM (1984) method for comparability is being used, the CTS needs to be within 10 m of the subject anemometer in the horizontal and the lesser of 1 m or H/10, where H is the height above ground in meters, in the vertical. It is important to site the CTS to be representative of the flow at the subject anemometer. Mutual interference should be minimized through siting and through editing out data where the direction shows the wind passing through one to reach the other. The accuracy potential of the CTS method is based on data taken in 1982 at the Boulder Atmospheric Observatory (BAO) and published by Finkelstein et al. (1986) and Lockhart (1988). The anemometers for this study were spaced about 5 m apart. The closer together they are in the horizontal the larger the direction sector of mutual interference.

The best situation for CTS auditing is one in which both anemometers are connected to the auditor's data logger. The element of the CTS audit is the difference in speed calculated by subtracting the CTS speed from the subject speed. The method requires a sufficient number of simultaneous and independent differences. A simultaneous difference is one where the time between sampling each anemometer output is less than 0.1τ, where τ (s) is found by dividing the distance constant, D (m), by the wind speed U (m/s). Independence is achieved when the time between sampled pairs is larger than 4τ. For example, assume the subject anemometer has a distance constant of 5 m and the CTS has a distance constant of 1 m. If the wind speed is about 3 m/s, τ will be 5/3 = 1.7 s for the subject and 1/3 = 0.3 s for the CTS. Simultaneous samples will exist when the sampling rate of the data logger is less than the shortest 0.1τ or 0.03 s in this example. Most data loggers are fast enough for the example.

Independence is achieved when the time between successive sample pairs is long enough. In the example above, 4τ is 20/3 = 6.7 s for the subject anemometer and 4/3 = 1.3 s for the CTS. If the CTS logger is set for one sample every 10 s, the data will be independent at 3 m/s. The ASTM method defines minimum sample size in terms of the resolution of the measured or reported speed (assume 0.1 m/s for the example, a recommended resolution) and the standard deviation of the series of differences. It takes 900 times the variance of the series to provide the minimum number. If the two sensors are well sited and properly operating, the variance will be small. The BAO data showed the standard deviation of the difference to be less than 0.2 m/s (variance of 0.04). This should be the minimum condition for a good CTS data set. If the variance is 0.04, the minimum sample size is 900 x 0.04 = 36.

Assume the subject anemometer produces a scalar average speed every 15 minutes and it is not possible to wire the output into the auditor's data logger. The CTS uses 90 samples, one each 10 s, to assemble its concurrent 15 minute scalar average. At this point, one can take one of two paths. One is to assume that the subject is operating well, has a short enough distance constant and is likely to agree well with the CTS on a sample to sample basis; not perfectly because a large bias can still have a small variance. There is no way to verify this assumption unless the audit results show good agreement. Based on this assumption, each 15 minute value is a data point with a sufficient sample size to compare the anemometers. Each datum point can be used in a linear regression analysis to define the subject anemometer's accuracy as a function of wind speed, if enough dynamic range exists in the data period. In just a few hours, then, the CTS method with this assumption will produce a measure of accuracy.

The other way is to treat each 15-minute average as a single sample of 15-minute averaged data. A 9 hour period will provide the minimum sample size of 36. This is an awkward period of time. It takes some time to install the CTS and many auditors work 8 hour days like other people. There is no such thing as too many samples. Added time usually enlarges the dynamic range for the audit. The optimum CTS audit goes for something like 24 hours, one diurnal cycle. For an example of this CTS audit, look at the data listed in Table 4.2.7.1.

Each value is a 20-minute scalar average. The subject anemometer is a Climatronics F460 cup (C-V-W). The CTS is a Young Propeller Vane (P-V-W) located 5 m away. Both are at a height of 10 m. The standard deviation of the CTS sensor is shown for each 20-minute period. The difference between the subject anemometer and the CTS is shown in the column headed by "Y-X." Notice that the average difference is a small -0.12 m/s and the standard deviation of the difference series is 0.10, half of the maximum criteria. To express the accuracy of the subject anemometer with respect to the CTS, a linear regression was run. The constant of 0.02 m/s says there is no bias of significance. The X Coefficient of 0.96 says that there is a 4 % underestimate of speed at all speeds. The best fit straight line through the Y points is calculated by multiplying the X (true) value by the coefficient and adding the constant. The residual error is then found by subtracting the X value from the estimated Y value, Y', (column headed by Y'-X). Notice that the average difference is 0.000, as it must be, and the standard deviation is lower, 0.07 m/s. The audit report for this subject anemometer would report the error of 4 % in the slope of the subject transfer function. (NOTICE: This is an example. The CTS is arbitrarily selected. It is possible that in this case the CTS was 4 % high or they were each off 2 %. That is not important for this example and the speeds are so close that this analysis was not included in the BAO experiment.) These data are shown graphically in Figure 4.2.7.9 and Figure 4.2.7.10. The anemometer data are shown on an XY plot with the best fit straight line through the 72 points. Figure 4.2.7.10 shows an XY plot of the residuals. Also shown is the normalized turbulence, σ_U/U (s/X in the table), plotted as a function of speed to look for correlations. There seems to be no influence of turbulence on the residual error.

The CTS method provides a measure of accuracy which can be related to wind tunnel tests (NBS and others). Some field audit devices which claim this capability must be used with caution (see Lockhart, 1985a). But the CTS method does not provide a measure of starting threshold. It is possible to get threshold data from a CTS audit if the CTS has a low enough threshold, say 0.5 m/s, and if periods are found with samples from the CTS sensors in the 0.6 m/s to 1.6 m/s range, for example. Suppose the subject anemometer reported 0.0 m/s or the 0.2 m/s offset value, indicating that it was not turning. The audit could report the subject threshold to be greater than 1.6 m/s. The best audit includes both the sensor control method and the CTS method for wind speed.

Table 4.2.7.1 Simulated Audit Data (BAO 1982)

9/82 Date/ Time	Y Subject Speed (m/s)	X CTS Speed (m/s)	s CTS Sigma (m/s)	s/X (m/s)	Y-X (m/s)	Y'-X (m/s)
4 1000	3.701	3.729	1.047	0.28	-0.03	-0.11
4 1020	2.972	2.979	2.441	0.82	-0.01	-0.10
4 1040	3.557	3.555	2.780	0.78	0.00	-0.13
4 1100	2.660	2.605	0.844	0.32	0.05	-0.14
4 1120	2.463	2.365	1.412	0.60	0.10	-0.17
4 1140	2.376	2.399	0.883	0.37	-0.02	-0.06
4 1200	3.210	3.344	1.951	0.58	-0.13	0.02
4 1220	5.511	5.623	3.230	0.57	-0.11	-0.10
4 1240	4.546	4.722	1.115	0.24	-0.18	-0.00
4 1300	4.261	4.555	1.319	0.29	-0.29	0.12
4 1320	4.157	4.455	1.348	0.30	-0.30	0.13
4 1340	3.127	3.250	1.120	0.34	-0.12	0.01
4 1400	2.364	2.433	1.557	0.64	-0.07	-0.01
4 1420	2.451	2.498	1.039	0.42	-0.05	-0.04
4 1440	4.176	4.270	5.887	1.38	-0.09	-0.06
4 1500	8.281	8.601	2.564	0.30	-0.32	-0.02
4 1520	7.678	7.893	1.638	0.21	-0.21	-0.10
4 1540	6.371	6.600	1.698	0.26	-0.23	-0.03
4 1600	5.569	5.976	2.847	0.48	-0.41	0.18
4 1620	3.346	3.413	3.537	1.04	-0.07	-0.05
4 1640	8.338	8.693	4.531	0.52	-0.36	0.01
4 1700	7.236	7.486	1.508	0.20	-0.25	-0.04
4 1720	5.425	5.588	0.751	0.13	-0.16	-0.05
4 1740	3.989	4.111	0.233	0.06	-0.12	-0.03
4 1800	4.399	4.617	0.820	0.18	-0.22	0.05
4 1820	4.407	4.615	0.930	0.20	-0.21	0.04
4 1840	3.847	4.012	0.345	0.09	-0.16	0.02
4 1900	3.941	4.121	0.291	0.07	-0.18	0.03
4 1920	4.344	4.474	0.151	0.03	-0.13	-0.04
4 1940	4.300	4.474	0.363	0.08	-0.17	0.01
4 2000	2.907	3.035	0.442	0.15	-0.13	0.02
4 2020	2.861	3.156	0.154	0.05	-0.29	0.18
4 2040	2.049	2.221	0.022	0.01	-0.17	0.10
4 2100	1.747	2.015	0.190	0.09	-0.27	0.21
4 2120	3.796	3.957	0.246	0.06	-0.16	0.02
4 2140	4.065	4.198	0.215	0.05	-0.13	-0.02
4 2200	3.885	4.031	0.137	0.03	-0.15	-0.00
4 2220	4.221	4.376	0.206	0.05	-0.16	-0.01
4 2240	4.097	4.261	0.292	0.07	-0.16	0.01
4 2300	4.037	4.194	0.194	0.05	-0.16	0.00
4 2320	3.952	4.135	0.144	0.03	-0.18	0.03
4 2340	3.559	3.717	0.109	0.03	-0.16	0.02
5 0	3.449	3.580	0.123	0.03	-0.13	0.00
5 20	3.179	3.290	0.035	0.01	-0.11	-0.01
5 40	3.840	4.040	0.199	0.05	-0.20	0.05
5 100	4.393	4.617	0.113	0.02	-0.22	0.05
5 120	3.822	3.955	0.881	0.22	-0.13	-0.01
5 140	2.198	2.219	0.520	0.23	-0.02	-0.05
5 200	1.680	1.742	0.059	0.03	-0.06	0.01
5 220	1.484	1.510	0.576	0.38	-0.03	-0.01
5 240	1.599	1.624	0.377	0.23	-0.02	-0.02
5 300	2.569	2.697	0.076	0.03	-0.13	0.04
5 320	1.662	1.696	0.341	0.20	-0.03	-0.01
5 340	1.769	1.934	0.190	0.10	-0.17	0.11
5 400	1.054	1.114	0.459	0.41	-0.06	0.04
5 420	1.471	1.455	1.217	0.84	0.02	-0.05
5 440	2.181	2.286	0.438	0.19	-0.10	0.03
5 500	1.338	1.419	0.680	0.48	-0.08	0.04
5 520	3.315	3.503	0.180	0.05	-0.19	0.06
5 540	3.060	3.212	0.220	0.07	-0.15	0.04
5 600	1.992	2.074	0.379	0.18	-0.08	0.02
5 620	1.765	1.836	0.336	0.18	-0.07	0.02
5 640	0.920	0.896	0.072	0.08	0.02	-0.04
5 700	0.636	0.523	0.280	0.54	0.11	-0.11
5 720	1.809	1.856	0.422	0.23	-0.05	-0.01
5 740	1.571	1.577	0.173	0.11	-0.01	-0.04
5 800	2.058	2.115	0.292	0.14	-0.06	-0.01
5 820	1.910	2.000	0.519	0.26	-0.09	0.03
5 840	1.181	1.165	0.345	0.30	0.02	-0.04
5 900	2.880	3.013	0.891	0.30	-0.13	0.03
5 920	4.286	4.402	0.537	0.12	-0.12	-0.05
5 940	3.839	4.000	1.752	0.44	-0.16	0.01
Average					-0.125	0.000
Standard deviation					0.100	0.069

Regression Output:

Constant	0.0233
Std Err of Y Est	0.0699
R Squared	0.9982
No. of Observations	72
Degrees of Freedom	70

X Coeff.	0.9576
Std Err	0.0048

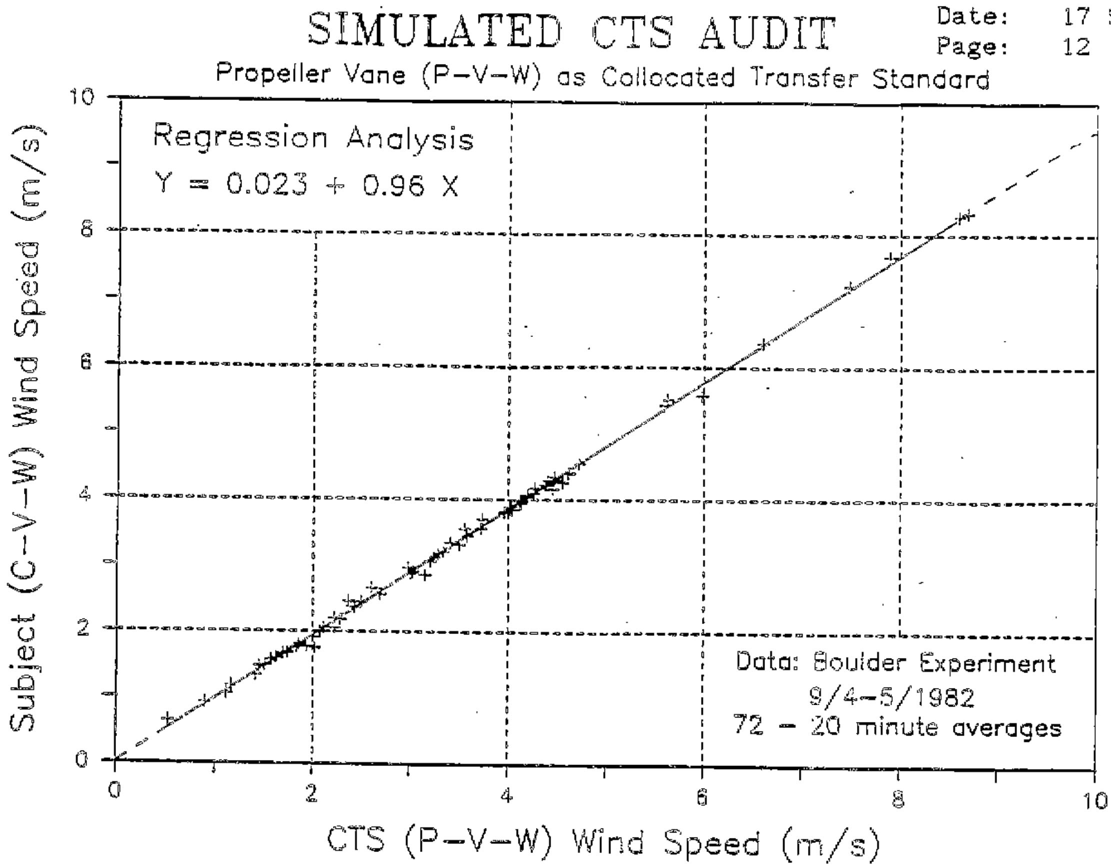


Figure 4.2.7.9 *XY plot of simulated wind speed audit data*

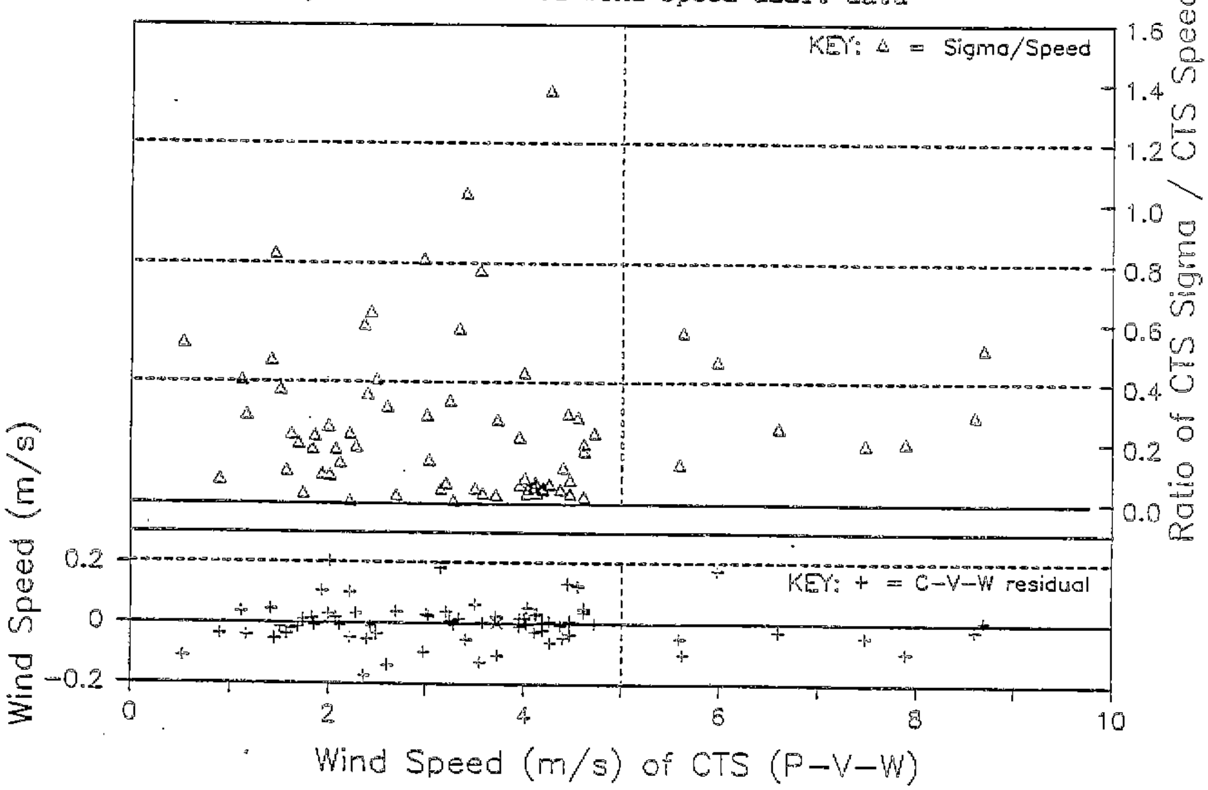


Figure 4.2.7.10 *Residual analysis of a simulated speed audit*

4.2.7.2.3 "W" Anemometers

Some stations measure the vertical component of the wind, with an anemometer sensitive only to the vertical component of the wind. A vertically mounted helicoid propeller, or "W" propeller, is the most common instrument for this measurement. The same audit methods can be used as are used on a propeller anemometer. A synchronous or d.c. motor will challenge the rate of rotation vs. wind speed and a torque device can be used to find the starting threshold. The common manufacturer's recommended practice is to use a different transfer function for the W propeller than the one applied when the same propeller is used for vane-oriented speed or for the N-S and E-W components of a UVW anemometer.

4.2.7.3 Wind Direction

4.2.7.3.1 Sensor control

The first thing to do on a performance audit of a direction vane is to record the as-found orientation value. Have the operator hold the vane so that it points to or from (whichever is most accurate for aiming) the distant orientation target. Verify the alignment by viewing the vane and target from the ground. Move back away from the tower or mast on a plane which passes through the sensor and the target and verify that the vane is in the plane also. Field glasses or a theodolite can help make this sometimes difficult observation. The vane must be held steady or clamped until a constant output exists for a few minutes. Record this value.

The controlled condition for a wind vane is a relative position of the vane with respect to the sensor housing. There are several ways to impose a series of known relative positions on the vane-sensor combination. They vary in effective accuracy. It is critical to know the time constant of the direction circuit BEFORE starting the performance audit. It can be measured by setting the vane to a known direction, simulate a wind from 090° holding the vane steady until the 090° (or voltage equivalent) output is steady. Move the vane quickly (< 1 s) to 270° and measure the time constant of the system. Assume that a time constant of 3 s is measured. Table 4.2.7.2 shows the change in output angle and voltage (assuming a 540° format and 5V output) as a function of time.

Table 4.2.7.2 - Time Constant Effects

Time Constant (No.)	Time Angle (sec.)	Vane Angle (deg.)	Output Angle (deg.)	Output Error (deg.)	Output (540@5) (volts)	Output Change (%)
0	0	090	090	0	0.333	0.0
0.2	0.5	270	106	164	0.981	9
1	3	270	204	66	1.889	63.2
2.3	6.9	270	252	18	2.333	90.0
3	9	270	261	9	2.417	95.0
4.6	13.8	270	268	2	2.483	99.0
6.9	20.7	270	270	0	2.498	99.9

(after Fritschen and Gay, 1979)

Notice that in this example a 180° shift requires waiting 20 seconds for the reading to be representative of the new position. If a 90° shift is used, 14 seconds will provide an output within 1° of the final value. If measurable time constants are found, suggest to the operator that the manufacturer be called about steps which might be taken to modify the circuit to a minimum time suitable for 60 Hz noise filtering.

The least accurate method for challenging the relative position accuracy of a wind vane is to point the vane in various directions while still mounted on the tower. This can provide positions related to external objects rather than constant angle changes. It is estimated that the accuracy of this method is two to five degrees, with the exception of a parallel alignment. The tail vane can be located parallel to a cross arm to within one degree, and held parallel on a calm day.

A second method puts the operating sensor in a controlled situation like a room where the electronics are located. The sensor can be placed at the center of a template with radial lines every 60°. The sensor can be oriented to the template and the vane moved and clamped when the vane is parallel to the radial line.. If care is taken to avoid parallax errors (non-parallel or non-perpendicular observations) this method can provide relative accuracy on the order of one degree.

The best method replaces the vane with a fixture with the capability of holding the shaft in fixed positions with respect to the sensor housing. Fixtures of this type can provide repeatable position accuracy of < 0.1°. Figure 4.2.7.11 shows such a device. A different application of this precise method uses a theodolite base as the mount for the sensor. With the vane or vane substitute held in one position, the base can be rotated in very accurate steps. Theodolite worm gear assemblies divide a circle in whole degrees with a vernier adjustment with 0.1 degree index marks far enough apart to allow easy interpolation to 0.02 degrees, a resolution wasted on the application of wind direction measurement.

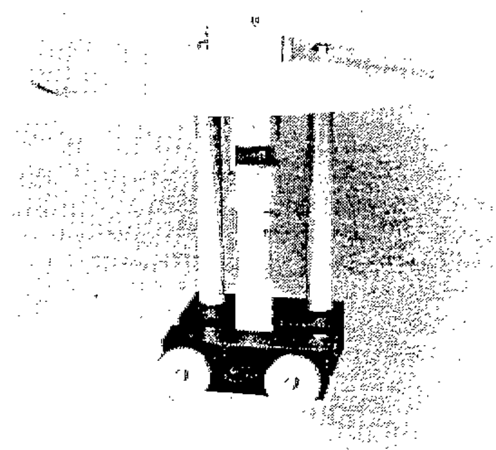


Figure 4.2.7.11

The audit report form should contain the transfer function used to convert output voltage to azimuth degrees. This may include a 540 format where azimuth values greater than 360 are reduced by subtracting 360. The report form should also contain the challenge progression used by the selected method.

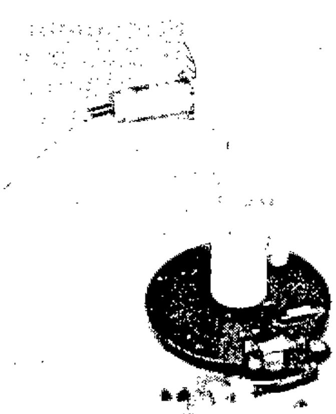


Figure 4.2.7.12

For example, Fig. 4.2.7.14 and Figure 4.2.7.15 show an audit method and audit form for wind direction which specifies 16 relative angles, each 60° from the last one, in a clockwise rotation for 420° followed by a counterclockwise rotation of 480°. This tests a 540 format, provides four samples at 180° (duplicates from each direction) and a duplicate counterclockwise 240° pair. The report of this series describes the range of relative error resulting from the shaft position measurement of the sensor (see 4.2.2.2.2.3 for an example).

The starting threshold of the bearing and transducer assembly should be measured by some method (see 4.2.2.2.1.2 and 4.2.2.2.1.3). If the k value is not available to convert the torque to threshold speed at some accuracy angle, the operator should be requested to ask the manufacturer to provide it for the next audit.

The bearing to the orientation target should be independently challenged with a method capable of better than compass accuracy. A theodolite is ideal for finding the bearing to other distant objects. A solar observation is recommended (see 4.2.4.3.2).

The last activity of the sensor control audit is to repeat the orientation test described above for the as-found value. The as-left value will represent any changes the operator may have made and the new orientation, if the sensor was not keyed for orientation.

4.2.7.3.2 CTS Method

There is no technical need for a CTS audit of direction. No new information is added by this method to that gained in the sensor control method. As a parallel example to the simulated CTS speed audit, data from the same period of time from BAO is shown here, structured as a simulated CTS direction audit. Table 4.2.7.3, sorted for ascending CTS direction, shows the 20-minute average direction for both the CTS (Young Propeller Vane, P-V-W) and the subject (Climatronics F460, C-V-W). Also shown is the σ_θ (or σ_A) for each 20-minute period. (See Lockhart, 1988, for a discussion of the impact of the sample size for σ_θ. The EPA required sample size for sigma calculations is 360. Only 180 samples were available in the BAO data) The mean and standard deviation were calculated from samples taken every 10 s. The difference in the mean for each period is listed under the heading "Y-X" and each period may be considered a valid audit, having met the requirement for a minimum number of simultaneous independent samples. Notice, however, that the 72 periods in the diurnal cycle did not include any averages from 001 to 107 degrees or 30 % of the dynamic range. The regression analysis is of little value for direction. The average difference of about 1° shows how closely they were oriented to TRUE NORTH. The standard deviation of the differences of 1.3° is smaller than the 2° suggested by Lockhart (1988) as the maximum variability for an acceptable CTS audit. Larger standard deviations must be investigated to find the problem in the subject vane. Properly operating vanes will meet that criteria. Figure 4.2.7.13 shows this "audit" data in graphic form. It is comforting to note that even with very turbulent conditions the vanes track each other on the average.

Table 4.2.7.3 Simulated CTS Direction Audit Data

9/82 Date/ Time		Y Subject Direction (deg.)	X CTS Direction (deg.)	s CTS Sigma (deg.)	Y-X (deg.)
5	740	110.72	108.58	39.34	2.13
5	720	126.18	121.60	20.76	4.57
5	1140	136.01	134.38	87.87	1.63
5	440	149.21	148.15	6.50	1.05
4	1000	170.93	170.74	27.02	0.18
4	1840	171.89	171.50	10.17	0.39
4	1820	175.12	173.71	30.55	1.42
5	1040	176.16	174.52	16.28	1.63
4	2200	175.63	175.24	7.62	0.39
4	2120	179.81	178.59	4.04	1.22
4	2140	180.49	179.64	10.87	0.85
4	1900	181.55	180.68	9.00	0.87
5	1100	183.77	182.95	13.26	0.82
4	1620	184.24	183.74	60.97	0.50
4	1720	186.51	185.29	6.10	1.23
4	1700	186.90	185.82	8.98	1.08
4	1740	187.74	187.07	6.66	0.67
4	1800	189.05	187.82	17.58	1.22
5	1020	189.53	190.19	27.04	-0.66
5	620	191.87	191.01	32.37	0.85
4	1640	193.01	191.43	9.24	1.59
4	1920	194.01	192.68	9.10	1.32
5	500	196.86	193.01	30.40	3.85
5	20	197.68	197.17	4.44	0.52
5	0	199.46	198.88	5.99	0.58
4	2320	201.43	201.11	6.94	0.33
5	1120	202.16	201.37	22.84	0.79
5	100	203.33	202.99	3.45	0.34
5	40	205.00	204.50	5.35	0.50
4	2300	205.77	205.64	6.21	0.13
4	2220	205.97	206.42	7.90	-0.45
4	2340	207.65	207.02	5.88	0.63
5	900	207.16	207.29	11.83	-0.13
5	120	209.25	209.08	9.57	0.16
5	920	212.67	212.72	9.31	-0.05
5	600	214.09	214.27	8.00	-0.17
5	420	214.12	215.12	20.18	-1.00
4	2240	216.04	215.95	5.86	0.08
4	1940	217.59	217.16	8.76	0.42
5	520	223.97	224.12	6.29	-0.15
5	220	229.65	225.55	17.04	4.10
5	540	227.38	228.04	9.38	-0.66
5	820	230.43	229.87	28.91	0.56
5	300	232.28	232.98	8.80	-0.70
5	320	239.91	237.14	25.28	2.77
4	2100	237.55	237.75	35.85	-0.19
4	1020	239.85	240.06	42.30	-0.20
5	940	239.28	241.26	63.08	-1.98
4	1140	242.97	244.21	29.30	-1.25
4	2040	247.28	248.22	12.10	-0.94
5	200	253.86	254.16	35.26	-0.30
4	2020	257.50	257.72	11.45	-0.22
5	400	260.27	257.80	20.16	2.47
5	340	264.41	263.64	12.57	0.77
4	1300	264.86	264.68	23.11	0.19
4	2000	267.01	266.10	29.16	0.91
4	1320	269.87	270.39	22.09	-0.51
5	140	273.76	273.13	43.68	0.63
4	1340	274.96	274.04	34.09	0.92
4	1600	275.77	275.35	21.27	0.42
4	1200	277.95	277.67	27.46	0.28
5	840	289.50	289.42	29.47	0.08
5	1200	299.15	297.87	11.74	1.28
5	800	300.55	298.01	65.04	2.55
4	1240	301.51	300.18	22.86	1.33
4	1220	310.99	308.24	17.77	2.75
4	1540	312.43	310.00	10.46	2.43
5	240	318.79	315.62	21.03	3.17
4	1520	324.82	322.49	12.26	2.33
5	1000	349.62	345.54	67.66	4.08
4	1440	359.13	355.74	30.58	3.40
4	1500	360.42	356.80	20.56	3.62

Average	0.91
Standard deviation	1.34

Regression Output:

Constant		-0.23090
Std Err of Y Est		1.33045
R Squared		0.99939
No. of Observations		72
Degrees of Freedom		70
X Coefficient(s)	1.00498	
Std Err of Coef.	0.00297	

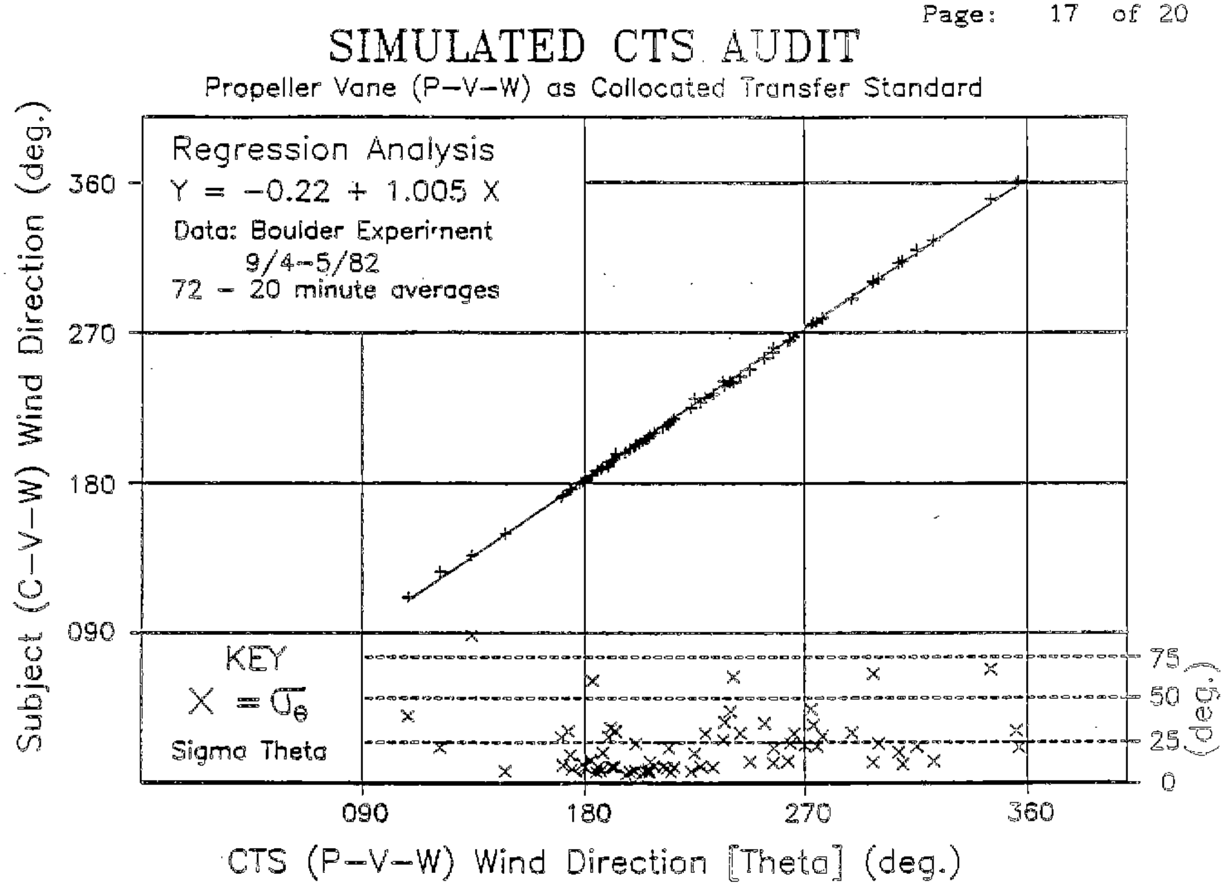


Figure 4.2.7.13 Simulated CTS Wind Direction Audit Data

4.2.7.3.3 Vertical Wind Direction, ϕ

The sensor control method is used for bivane auditing. The vertical part of the bivane operation is treated in the same way as the horizontal part, except different fixtures are used. Special fixtures are required for each bivane design, but the principle is the same. A relative zero point is set when the fixture is attached to the bivane. That point is where the vane shaft is perpendicular to the vertical axis of the sensor. From this starting point where the output should be the equivalent of 0°, the vane is held in 15° steps until its physical limits are reached, both tail up (+) and tail down (-). Threshold is very hard to measure on a bivane because of the static balance conditions of the vane. If the vane is perfectly balanced and its remains where ever it is physically moved, a force gage measurement at some distance from its axis of rotation will yield the starting threshold just as the vane begins to move.

4.2.7.4 TURBULENCE OR σ_θ and σ_ϕ

The measurement discussed in this section is θ or ϕ. The sigma values result from how the samples are combined to estimate the statistical parameters. It is a part of the auditor's job to determine how the algorithm works and to challenge that process with a known input. This is also a functional way to document the impact of the signal conditioning time constant on the measurement of direction variability.

The challenge should be realistic or at least within some realistic range. The challenge must take into consideration the wave shape of the variable direction imposed on the system in calculating the true sigma value with which the output will be compared. The effective time constant of the direction system, calculated from the delay distance of the sensor and some nominal wind speed important to air pollution applications, should define the maximum frequency used in the sigma challenge.

Wind Vane - MSI method WV004 (version 8/1/84)

This method describes the relative performance of the wind vane as a shaft-position transducer and the orientation of the transducer with respect to true North. The former is done with a fixture, part of which is mounted to the transducer body and part mounted to the shaft in place of the vane. The latter requires a determination of true North (see MSI method SN008) and a setting of the transducer relative to that orientation.

The report form for this method includes space for the optional method to define the "open space" where relevant to the sensor and application. Also there is space to record starting torque measurements and system time constant estimates for turbulence measurement.

WV004-A Remove the wind vane assembly (vane, shaft and counter-weight). A 1/8" shaft is required. If the sensor does not use that size or it is not accessible, an interface fitting is required. Mount the disc on the vertical shaft. Mount the clamp to the support column for the shaft so that the pin engages the disc and the disc is free to move when the pin is withdrawn. Set the fixture parts with the pin in the 180 degree hole. Rotate the clamp until the output indicates 180, either by equivalent voltage or digital printout. Since this is a position measurement, the challenge is constant and instantaneous values may be used, being sure to react to the needs of the time constant for stable readings. Move the disc (vane substitute) to the following positions taking data at each point: 120, 060, 360, 300, 240, 180, 120, 180, 240, 300, 360, 060, 120, 180, and 240 degrees. This moves the "vane" 420 degrees counter clockwise and then 480 degrees clockwise to test "540" strategies for the angle discontinuity.

WV004-B Define the "open space" for 360 degree potentiometer transducers. Install the index line fixture to an appropriate position with respect to the protractor mounted to the disc. Disengage the pin. Rotate the disc until the output changes from maximum voltage to five degrees less than maximum. Record the angle to 1/2 degree resolution. Rotate the disc back toward maximum voltage and record the angle when maximum is first reached. Rotate the disc until the output changes from minimum voltage to five degrees greater than the minimum. Record the angle. Rotate the disc back toward the minimum voltage and record the angle when minimum is first reached.

WV004-C After having found a distant target of known direction (see SN008), set the vane so that the direction is the output of the sensor. Clamp the vane to the shaft support tube so that the output stays constantly correct, even with light wind forces on the vane. In heavy wind, a fixture replacing the vane is required. Place the sensor in its mount and rotate the sensor body until the vane counterweight points to the target. Clamp the sensor in place, check the output and remove the vane clamp. Record one system data point with all cables in place and the sensor clamped.

Figure 4.2.7.14 *A method for auditing a wind direction sensor*

PERFORMANCE AUDIT REPORT by ______________ WV004

MEASUREMENT SYSTEM - Wind vane
System number ______________
Sensor ______________
Vane ______________
Location ______________
Signal conditioner ______________
Data channel ______________

DATE __/__/__ TIME off line _____ on line _____ test start ___

TRANSFER FUNCTION (volts per degree) ______________
discontinuity strategy ______________

TEST RESULTS

WV004A (dif. = deg. - set)

set	volt	deg.	dif.	set	volt	deg.	dif.	set	volt	deg.	dif.
180	____	____	____	240	____	____	____	300	____	____	____
120	____	____	____	180	____	____	____	360	____	____	____
060	____	____	____	120	____	____	____	060	____	____	____
360	____	____	____	180	____	____	____	120	____	____	____
300	____	____	____	240	____	____	____	180	____	____	____
								240	____	____	____

WV004B

1				2				
volt	deg.	angle	dif.	volt	deg.	angle	dif.	abs((1-2)-360)
____	____	____	____	____	____	____	____	-10 = ____
____	____	____	____	____	____	____	____	____

Torque: _____ Oz.-In. cw, _____ Oz.-In. ccw, T. Const._____s.

WV004C

time	expected		obs. before (1)		obs. after (2)		difference
	volt	deg.	volt	deg.	volt	deg.	(2-1) deg.
____	____	____	____	____	____	____	____

Figure 4.2.7.15 . *A form for the wind direction audit method*

4.2.8 ESTIMATING ACCURACY AND PRECISION

4.2.8.1 Measurements

Section No. 4.1.5 contains a detailed discussion of methods of estimating accuracy, precision and bias using wind speed and wind direction as examples. That material will not be repeated here. The measurement process begins with an instrument which has some element or part which is sensitive to the variable of interest. If interest is in air flow with respect to the surface, there are two variables, wind speed and wind direction. Each part of this section discusses various aspects of how the measurements might be made, calibrated, operated, maintained and documented to support a claim of measurement validity. It is recognized that instruments are usually parts of data systems with sampling, processing and summarizing routines designed to produce final elements of a data base to be used for some application. The earlier parts of this section were devoted to methods of tracking the measurement process all the way through the system to the system output. Accuracy was addressed in terms of how well what was designed to be done was actually done. The second part of this sub-section will deal with how well the system design serves the application.

4.2.8.2 Summarized Data

Summarization schemes are many and preclude a full discussion here. The auditor should define the methods used and comment on the appropriateness of the method to the application of the summarized data. There may be concurrent summarizations such as a scalar wind speed, a resultant vector wind speed and some kind of summarized wind direction. The accuracy of the data system should reflect estimated errors because of an inappropriate summarization program.

A software analysis is required to be sure that the declared method of summarization is in fact being accomplished by the computer program. For example, is the scalar average wind direction avoiding the error of averaging a circular range with a discontinuity? If the average of winds ranging between 300° and 060° turns out to be about 180°, this problem still exists.

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Section 4.3
QA FOR TEMPERATURE AND TEMPERATURE GRADIENTS (ΔT)
OUTLINE

QUALITY ASSURANCE FOR TEMPERATURE AND TEMPERATURE GRADIENT (ΔT)

4.3.0 SUMMARY

The measurement of temperature is standardized in great detail by all those organizations interested in such procedures, ASTM, ISA (Instrument Society of America), and TMS (Temperature Measurement Society). The problem with meteorological applications is that the free air temperature is required. This means the transducer needs to be exposed to the atmosphere which is in turn exposed to the sun about half the time and to the very cold outer space the other half. The atmosphere is conditionally transparent to heat sources (the sun) and sinks (outer space) so shielding must accommodate a wide range of radiative conditions. Wind also influences the temperature shield. It transfers heat to and from the shield in a variable way as a function of wind speed. Most effective shields use forced aspiration to expose the transducer to nearly unmodified outside air. Wind speed may also play a variable role in the performance of the aspiration system.

This section concentrates on the meteorological applications of air temperature measurement and the differential temperature measurements which are interpreted as temperature gradients and applied as a measure of vertical stability.

Since the application of the measurement should define the accuracy needed, both the relatively course air temperature and the relatively fine temperature difference measurements will be considered.

4.3.1 TYPES OF INSTRUMENTS

There are several materials and structures which change in some way as a function of temperature. General books on meteorological instruments such as Mason and Moses (1984), Middleton and Spilhaus (1953) and particularly Brock and Nicolaidis (1984) will provide details on a variety of these sensors. From the standpoint of quality assurance, a few basic principles and a few standard types will represent the vast majority of instruments in use for air quality applications.

The measurement of temperature for air quality applications is generally thought of as either air temperature, T, or a difference between two temperature measurements, ΔT. The application of these different measurements require different specifications and auditing methods. The two types of temperature measurement will be treated in later sections as separate measurements.

Temperature instruments are made up of three important parts. The transducer is the device which changes its electric value as a function of the temperature of the transducer element. The signal conditioner and cables convert the electric value to a recordable output, usually volts. The aspirated radiation shield is the mounting structure which holds the transducer in the atmosphere where the temperature is to be monitored. Each of these three parts will be discussed separately since there are various combinations possible.

4.3.1.1 Transducers

Consider the transducer as the part containing the sensing element. In most cases, the sensing element is the transducer in air quality monitoring applications. The element is usually a thermistor (or thermistor network) or a winding of fine wire on an insulated bobbin. It could also be a thermocouple or a circuit element like an integrated circuit (see Cole, 1978). The elements are usually encased in a protective capsule and sealed. From an operational standpoint it only matters how the sensor reacts to the temperature inside the aspirated radiation shield.

4.3.1.1.1 Thermistors

The thermistor is an electronic semiconductor made from certain metallic oxides, such as nickel, manganese, iron, cobalt, copper, magnesium, titanium and other metals. It is a nonlinear element. One common supplier (Yellow Springs Instrument Co. [YSI]) sells both the standard thermistor and the "linear" thermistor. Table 4.3.1.1 shows a typical negative thermal response curves of raw thermistors and the nearly linear response of the network thermistor. Also shown is the positive response of two platinum RTD (resistance temperature detector or resistance thermal device) for contrast. Notice the large average change per °C with the YSI bead thermistor between 10°C and 20°C (222Ω) as compared to the network thermistor (126Ω) or the 100Ω RTD (0.4Ω) or the 1000Ω RTD (3.8Ω). The raw bead thermistors are included because, in the future, microprocessor-based data systems can handle nonlinear transducers as easily as linearized ones. The "linearized" YSI has a small oscillating error of about ± 0.1°C with a wave length of about 40°C. The impact of this error on temperature difference systems is small. At the

Table 4.3.1.1 - Sensor Resistance vs. Temperature

	Thermistors				Platinum RTDs			
	------YSI------		------YSI-----		----MINCO----		----HY-CAL----	
T	44031		44203 network		5-100 Pt		1000Ω Pt	
(°C)	(ohms)	(ΔΩ)	(ohms)	(ΔΩ)	(ohms)	(ΔΩ)	(ohms)	(ΔΩ)
-10	16600		13438		96.09		961.84	
		-684.0		-127.9		0.391		3.816
0	9796		12159		100.00		1000.00	
		-382.5		-125.3		0.390		3.804
10	5971		10906		103.90		1038.04	
		-222.3		-126.1		0.389		3.792
20	3748		9645		107.79		1075.96	
		-133.1		-128.6		0.388		3.780
30	2417		8359		111.67		1113.76	
		-81.9		-128.8		0.387		3.768
40	1598		7072		115.54		1151.44	
		-51.7		-123.6		0.385		3.756
50	1081		5836		119.39		1189.00	

(ΔΩ) is ohms per degree C for the 10 degree range
YSI-------Yellow Springs, OH 45387
MINCO-----7300 Commerce Lane, Minneapolis, MN 55432
HI-CAL----9650 Telstar Ave. El Monte, CA 91731-3093

steepest slope it is 0.025°C per degree difference. A ΔT would need to be ± 4°C before the error reaches 0.1°C, at which point the error is moot with respect to application.

The big advantage to thermistors is the relatively large resistance of the element with respect to the resistance of the signal cable. Lockhart and Gannon, 1978, pointed out the fact that it would take a 12.5Ω difference in cable resistance to two sensors of a ΔT pair to cause a 0.1°C error (bias) in the ΔT measurement. Most signal conditioning circuits have the capability of adjustment to eliminate such a bias. Another little known advantage is stability. A several year stability test conducted at NBS showed thermistors to be extremely stable. This is contrary to early experience which suggested that thermistors often failed with a shift in the transfer function (ohms vs. temperature) gaining them a reputation of instability. Better packaging designs and better handling practices have eliminated many of these problems.

4.2.1.1.2 Wire bobbins

The resistance of a wire changes with temperature. If a long piece of fine wire can be handled in some way, it can be used as a temperature element. Winding the wire on a non-conductive bobbin is the traditional method of handling. When the bobbin is large and open, a very fast response sensor is made. When the bobbin is potted in a stainless steel jacket, a more traditional slower response sensor is made. The transducer in both cases is a length of wire. Different metals have different temperature coefficients. A

40 gauge (0.08 mm diameter) wire at 20°C made of annealed copper has a resistance of 3.4Ω/m. If it were made of German silver the resistance would be 65.9Ω/m. Platinum and iron are each 20.0 Ω/m while nickel is 15.6 Ω/m. Manufacturers, choosing for stability, ease of handling and cost for a suitable resistance, have settled on a few materials. Platinum (100Ω) is the most common for meteorological applications. Nickel-iron is another common wire providing a higher resistance at a lower cost with good stability.

Because of the small resistance change for a 1°C temperature change (0.4Ω), the transducer resistance must be measured with both high resolution and attention to cable resistance. Three and four wire bridge circuits are commonly used, the latter being best for handling long cables. It will be shown in the sections on calibration and auditing that many of the details of the transducer and circuits need not be known. Only the system performance is important.

4.3.1.1.3 Mercury-in-glass thermometers

These thermometers are not transducers, but they are commonly used for calibrations. Some styles have enough resolution to be read to 0.02°C with some care. The ASTM series of Precision thermometers are examples of these. They are 37.9 cm (15 inches) long and breakable (and expensive - $50 to $80 each). They are also calibrated for total immersion. The ASTM 62C has a range from -38 to +32°C and scale divisions of 0.1. The ASTM 63C has a range of -8 to +32°C and also has scale divisions of 0.1, but they are farther apart making interpolation more accurate. If higher temperatures are needed, the ASTM 64C has a range of 25 to 55°C.

4.3.1.1.4 Thermocouple systems

The thermocouple operates on the principle that when two different metals are joined, a small voltage with a temperature- dependent magnitude is generated. By comparing this voltage to the voltage generated by a second thermocouple in a thermally stable environment of known temperature, the temperature of the first thermocouple can be determined. Because of complex circuitry and problems with conductors, thermocouple systems are no longer popular transducers for meteorological monitoring.

Thermocouple pairs are well suited for differential temperature measurement. They provide the same voltage for any size wire which makes them ideal for miniature fast response applications.

4.3.1.2 Signal Conditioning

There are a multitude of circuits which will measure resistance. Usually the transducer and the signal conditioner are purchased as a system, complete with interconnecting cables. This is advisable since the range of resistance vs. temperature is quite large. Signal conditioning circuits may be adjusted to conform to individual transducers or transducer pairs. They may also be adjusted to a generic or theoretical curve or transfer function. It is important to understand the function of the signal conditioner and to treat it as a part of a system along with the transducers and the cables.

4.3.1.3 Aspirated Radiation Shields

There are many kinds of shields, as Figure 4.3.1.1 depicts. Most of the error in measuring air temperature comes from the shield. It is also true that the magnitude of the error is largely unknown. In Section 4.3.2 SPECIFICATIONS, there is a detailed discussion about accuracy of shield performance.

The measurement of the temperature of the free atmosphere at the point where the shield intake is located is the goal. A shield protects the sensor from radiation and provides the mechanical mount for the sensor on a tower or mast. If the shield is not aspirated, or designed for effective natural ventilation, it may become little more than a larger sensor case resulting in the same radiation errors as an unshielded sensor but with a longer time constant. To avoid this difficulty, it is necessary to draw the air into the shield in such a way that it is not modified by the shield temperature but will come to equilibrium with the transducer at some average time.

Forced aspiration is the only way to minimize radiation error for all conditions. A fan draws air in past the transducer at a speed suitable for minimum error. Forced aspiration can be designed to provide a flow in the right direction under all ambient wind conditions. Insufficient pressure drop in the fan during strong winds may allow reverse flow to occur transporting the heat from the fan back to the transducer (Lockhart, 1975).

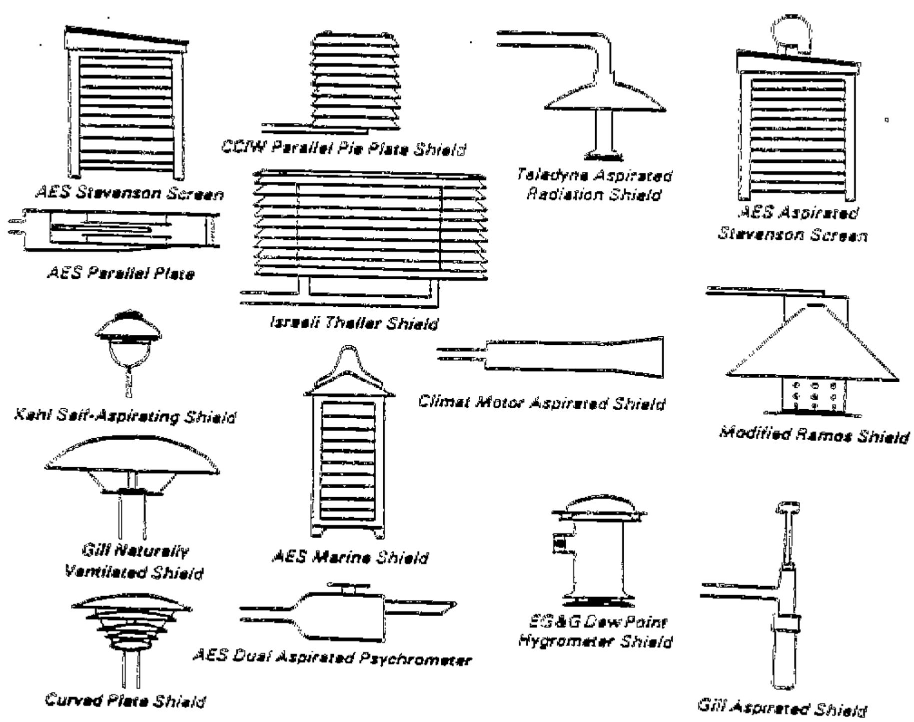

Figure 4.3.1.1 *Examples of various radiation shields (McKay and McTaggart-Cowan, 1977)*

4.3.2 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.

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 for temperature are range and accuracy. The performance of the radiation shield is not defined by specification. There is an implication that the accuracy requirements include this error source, but if they do there is no way suggested to verify the performance of the shield.

4.3.2.1 Delta Temperature (ΔT)

The only requirement in EPA (1987a) regarding the vertical temperature difference is "Errors in measured temperature difference should not exceed 0.003°C/m." This rate is based on a 0.15°C accuracy for a 50m separation. The requirement came from a time when ΔT was traditionally measured between the lower 10m level and the upper 60m level on a tower. If a shorter tower is used, like a 44m tower, the separation between 10m and 44m, namely 33m, would show smaller lapse rates and inversions. If the same accuracy were to be preserved in measuring the equivalent or representative ΔT from the shorter tower, the measurement accuracy had to be better, 0.1°C in this case. Some operators went to even shorter towers and to assure an appropriately accurate measurement system, the requirement was stated as a per meter error.

The above requirement is impossible to meet with the new 10m towers including ΔT. If the aspirated radiation shields are mounted at 2m and 9m (to avoid interference with the 10m wind), the requirement is to not exceed an error of 7 x 0.003 = 0.021°C. This is an accuracy which is hard to prove, let alone achieve.

The dynamic range for a ΔT installation on a 60m tower might be from -2°C to +15°C. Convention for positive and negative ΔT is:

(-) a lapse rate is the normal decrease of air temperature with height limited by the auto convection rate of 3.4°C/100 m or 0.034°C/ m. A lapse rate produces a negative ΔT.

(+) an inversion is the inverted lapse rate or an increase of air temperature with height. There is no limit for inversion strength. An inversion produces a positive ΔT.

The dynamic range between 2m and 9m is not much different than that between 10m and 60m. During the EPA-BAO experiment in 1982 (Lockhart, 1988), a pair of ΔT sensors was mounted on tower 4 at 2m and 8.6m. Each sensor was a 100Ω Rosemont platinum RTD in a Young aspirated shield. On tower 3, also at 2m and 8.6m, a pair of MRI-YSI linearized thermistors mounted in MRI shields (patterned after the Young shields) were operated. Figures 4.3.2.1 and 4.3.2.2 show three days of 20-minute average ΔT data and 2m temperature data from tower 3. Also shown

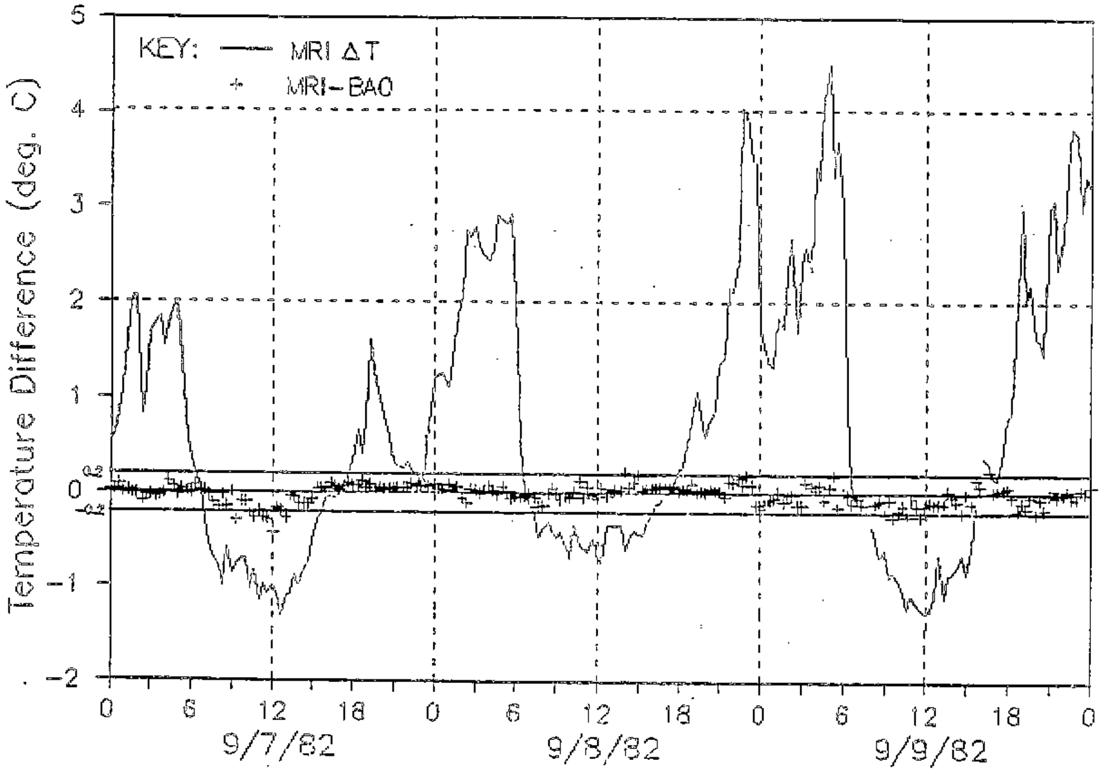

Figure 4.3.2.1 *MRI ΔT Data and ΔT Difference Data for Three Days*

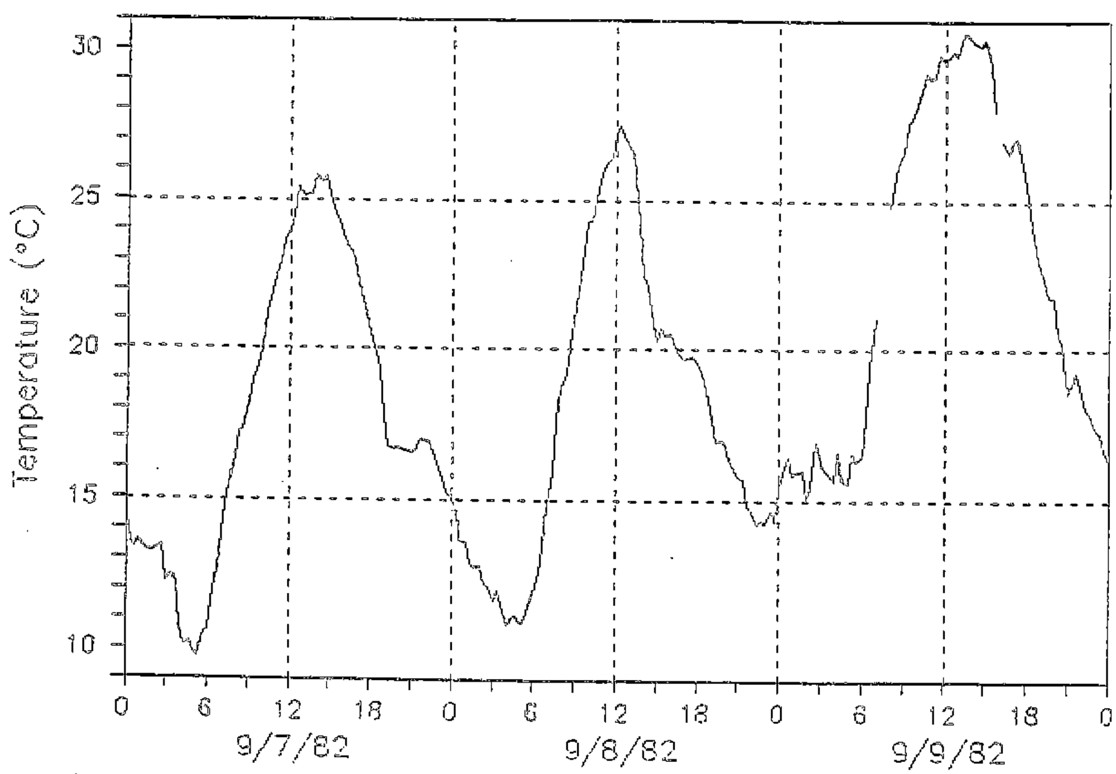

Figure 4.3.2.2 *Air Temperature at 2 m from the MRI ΔT Pair*

is the difference between the two 20-minute average ΔT measurements from the two towers. Note the dynamic range of -1.3°C to +4.5°C (per 6.6m) and the agreement between the two different instrument systems. For the three days the average difference is -0.02°C with a standard deviation of 0.10°C. The daily temperature range was about 17°C.

The reason the dynamic range is so high for such a small separation distance is that the surface is a better radiation receiver and transmitter than is the air immediately above it. The surface is almost always hotter or colder than the air above it. Convection and mechanical turbulent mixing drive almost all of the heat flux between the surface and the air. The closer the sensors are to the surface the larger the temperature difference per meter of separation. The drawback is that the closer the ΔT pair is to the surface the more sensitive the differential measurement is to local surface conditions or character. A black top road will affect a 2-10m ΔT much more than it will affect a 10-60m ΔT. The lower sensor really drives the ΔT and a 2m temperature will vary more than a 10m temperature.

For these reasons, the suggested procurement specification in the On-Site guide (EPA, 1987b) in 8.1.3 reads:

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

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

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

Data sheets from five manufacturers (listed alphabetically) specify their aspirated radiation shields as follows:

1. Climatronics TS-10	Under radiation intensities of 1100 W/m^2 measurement errors due to radiation will not exceed 0.1°C. Aspiration rate 3 m/s at sensor location.
2. Met One 076	Radiation error -less than 0.05°F (0.03°C) under maximum solar radiation of 1.6 gm-cal/cm^2/min (1100 W/m^2). Flow rate 500 ft/min (2.5 m/s).
3. Qualimetrics 8150-A	Radiation error - 0.05°C during maximum aspiration and full sun. Air speed 360 ft./min. (1.8 m/s).

4.	Teledyne Geotech 327C	Shielding - Under test radiation flux density of 1100 W/m^2 errors caused by radiation are less than 0.1 °C. Aspiration rate 6 m/s at sensor location.
5.	R. M. Young 43408	Radiation error - under radiation intensity of 1080 W/m^2, Ambient temperature - 0.2 °C RMS, Delta T - 0.05 °C RMS with identical shields equally exposed. Aspiration rate - 3 m/s.

It is difficult not to notice the similarity among these very different designs. An auditor would need a comparative field test to find the relative error from solar radiation. Such a test can be done using a ΔT sensor pair with two (or more) shields collocated at the same level. If the transducers are well calibrated, the relative temperature of the transducers can be known to 0.02 °C. these transducers in the two aspirated radiation shields will report the relative performance of the shields to the same relative accuracy. The one which is coolest in the daytime and warmest at night has the least radiation error. Several diurnal cycles with sunny days and clear nights are required. Such a test series could identify the most efficient shield which could become a standard against which a relative error analysis of any shield could be made by a CTS method.

4.3.2.2 Temperature

The accuracy specification for temperature is suggested in EPA (1987b) as

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

Some applications such as "PSD" permits without fog problems require an accuracy of only 1 degree C. For locations with winds generally above 1.5 m/s, a well designed naturally aspirated shield can provide 1 degree C. accuracy. When the application requires an aspirated radiation shield, the shield performance requirement should also be included in the specification. It is customary to use the lower ΔT shield to aspirate both the temperature and half the ΔT pair. Some designs develop ΔT by subtracting one temperature measurement from the other, in which case there is only one sensor in the lower shield.

4.3.3 ACCEPTANCE TESTING

There are two ranges of temperature to consider. One is the measurement range and the other is the environmental operating range. The two might be similar for remote installations without commercial power or air conditioned shelters. The operating temperature range of the signal conditioning circuits for remote installations is a function of the radiation shielding of the electronics and the heat generated by the circuit operation. The electronics may get both colder and hotter than the air temperature under these circumstances. The operating temperature range for a station with an air conditioned shelter is much narrower than the measurement range. The receiving or acceptance test design must consider these factors. A conventional temperature chamber is required to control the temperature of the electronics while the sensors are controlled by a separate thermal environment.

A test which demonstrates the operation of ΔT and T sensors connected to their signal conditioners is recommended. The test should include at least two temperatures. Liquid bath or solid thermal mass devices are recommended to avoid local gradients in the air. It is necessary to remove the sensors from the aspirated radiation shield and place them in a bath while they are still connected to the signal conditioner. This may prove difficult to do with some designs. Since calibrations and audits are likely to require the same accessibility of the sensors in the field, it is best to solve this potential difficulty in the less hostile receiving laboratory space. Perhaps a statement of accessibility needs to be included in the specification.

Experience has demonstrated that thermal stress can cause sensor failure when baths are used. The sensors may seem to be sealed, but if a sensor is submerged in a hot (40°C) bath for enough time to reach equilibrium and take a series of measurements, and then submerged in a cold (0°C) bath, the pressure change inside the metal sensor cover may draw water into the element chamber.

It is prudent to assume that the sensors are not hermetically sealed and to protect them as much as possible. Using solid thermal mass devices is one way to avoid liquid from wicking or being drawn into the sensor, but it is not a total protection. In the above example, room air may be drawn into the cooling sensor as the pressure inside equalizes with ambient pressure. The air drawn in may be saturated at the new cold temperature or may condense some water vapor. Whether or not this is a problem depends on how the sensor is made, but it is best to take what precautions are possible. If complete immersion is necessary, wrap the sensors in plastic so no liquid can get to the interface where the wires come out of the sensor. Use partial immersion where possible keeping the interface dry. Keep temperature changes small and in the order AMBIENT→COLD→ AMBIENT→HOT→AMBIENT.

Assume the receiving test will use two temperatures, ambient temperature and an ice slurry. Assume a water bath will be used for the ambient test. If one to three sensors are in the system, wrap them together along with a thermometer using a rubber band. Use a Thermos® bottle which has been filled with water several hours earlier. The key to accurate temperature measurements with sensors of different time constants is in having a thermal mass with minimal gradients. The value of a Thermos bottle is its long time constant. It will tend to keep the temperature of its contents constant, but all it can do is cause the heating or cooling to be slow. In time the contents will be at the same temperature as the surroundings, if the temperature of the surroundings is constant, like an air conditioned room. When this equilibrium has been reached, the water in the bottle will be at the same temperature everywhere in the bottle and stirring is unnecessary. Stirring suggests the need to mix up parts of different temperature. It is better not to have parts of different temperature and this can be achieved by reaching equilibrium with a well insulated mass.

Place the sensors and thermometer into the Thermos. Use a cork or some cover to keep ambient air from circulating over the top surface of the water mass. After about 30 minutes, assume the sensors and thermometer are in equilibrium (they should be, they went in from the same equilibrium temperature) and start a series of measurements. Take five measurements about five minutes apart. If the measurements are constant rounded to the nearest tenth degree C, average the five readings and use them to describe the temperature with respect to the thermometer and ΔT with respect to zero difference. If the measurements are slowly increasing with respect to the slower thermometer, there is a self-heating error. Any resistance element will get warm when current flows through it. It is expected that the self-heating will be small and the large thermal mass will carry the heat away without detection. It is also possible that the elements are sampled and do not have current flowing continuously. If self heating is detected, or if you wish to shorten the time to equilibrium, some mixing of the water in the Thermos may be useful.

After the response to ambient temperature has been recorded, place the assembly of sensors and thermometer in a Thermos bottle containing an ice slurry. The ice should be made with distilled water and crushed into pea sized pieces and mixed with distilled water until an easily penetrable slurry is reached. As long as ice is present at the bottom of the Thermos, the temperature of the slurry will be $0.0 \pm 0.1^{\circ}C$. Within 15 minutes to one hour, equilibrium should be reached. A series of five measurements taken five minutes apart should be recorded. If the measurements support the assumption of equilibrium, then the five readings are averaged and recorded as the temperature relative to $0.0^{\circ}C$ and the thermometer, and ΔT with respect to zero difference.

Accurately reading the meniscus of the thermometer requires two things. One, is the ability to see the meniscus and the scale at the same time. Magnification is helpful even for those with good eyes. It makes the interpolation between scale marks possible and accurate. Secondly, the eye must be perpendicular to the meniscus to avoid parallax errors. If a mirror is held against the back side of the thermometer and the center of the image of the eye moved to the meniscus level when the scale is read, the perpendicular requirement will be met.

4.3.4 INSTALLATION

Each design of aspirated radiation shield has its own installation requirements. The manufacturer's manual must be used in addition to the general guidance given here.

The installation location is chosen to represent the temperature relevant to the application. The height above ground is the first consideration. If the temperature is to be used for climatological purposes, a 2m height above a grass surface will do. If the temperature is to be used to describe the air being drawn into a manifold for chemical analysis, the best location is the one that represents what the manifold inlet "sees." If a temperature gradient is to be used to describe the stability of the surface layer, a representative pair of heights is selected. Siting is best done with the concurrence of the person who will be using the data for analytical purposes, the person who will judge the data to be valid, and the person who will accept the data and the analysis on behalf of the regulating agency. Siting by this committee approach will benefit from any objective knowledge any member might have, but its strong point is in the mutual understanding of the criteria which were used in making the selection.

The second consideration is bias from surrounding structures. The temperature that is measured is that of the air which is drawn into the aspirator. If there is a prevailing wind, mount the radiation shield into the wind such that the wind passes the shield before reaching the tower. The farther the aspirator inlet is from the tower, the smaller the angle segment which can contain the tower heat and the more mixing with non-heated air by the time the inlet is reached. The distance out from the tower should be the maximum allowed by the mounting hardware. Special booms for temperature may be necessary if the design does not provide for siting the inlet at least one tower diameter from the edge, and if 0.5°C accuracy is expected.

4.3.5 CALIBRATION

The manufacturer's manual will give instruction for the adjustment of signal conditioning circuits in response to some input specification. Usually what is required is a precision resistor, either built in or to be supplied by the calibrator using a decade box or equivalent. Such procedures are assumed to have been done and will not be discussed here. The method recommended in this handbook is independent of the manufacturer. It requires only the generic transfer function of the resistance element used, that is the ohms vs. temperature relationship upon which the measurement system depends for accurate performance.

4.3.5.1 Calibration Equipment and Methods

The handbook method requires three stable thermal mass assemblies with temperatures known to about 0.1°C. The three masses may be one mass used three times with sufficient time allowed for conditioning to a new temperature. Sufficient effort must go into the determination of thermal stability and accuracy of the temperature measuring system used for that determination in order to defend the results of the calibration or audit. The following will describe one solution to this requirement. This solution is not the only one but the confidence in stability and accuracy produced by this solution is an example of the documentation necessary to support claims of accuracy.

The thermal mass design uses a solid aluminum cylinder, shown in Figure 4.3.5.1, chosen for high thermal conductivity. The mass is supported in the space inside a stainless steel insulated bottle (see Figure 4.3.5.2) by a lucite tripod on the bottom and by three low thermal conductivity stainless steel screw spacers at the top. The lid is modified to allow transducer cables to go through. The insulating bottle is positioned inside a 2-gallon insulated container modified to allow cables to go through with the top in place as shown in Figure 4.3.5.3.

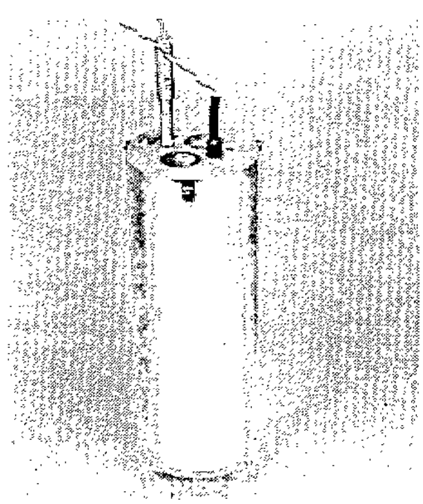

Figure 4.3.5.1 *Thermal Mass*

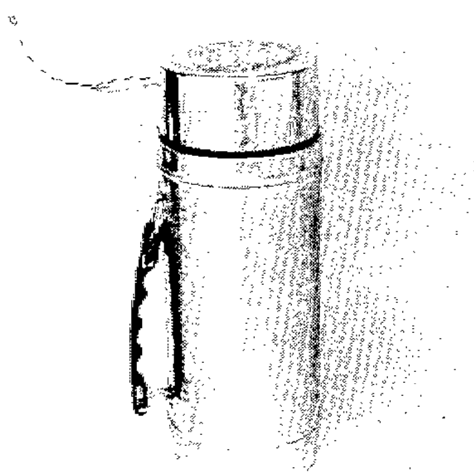

Figure 4.3.5.2 *Insulated bottle*

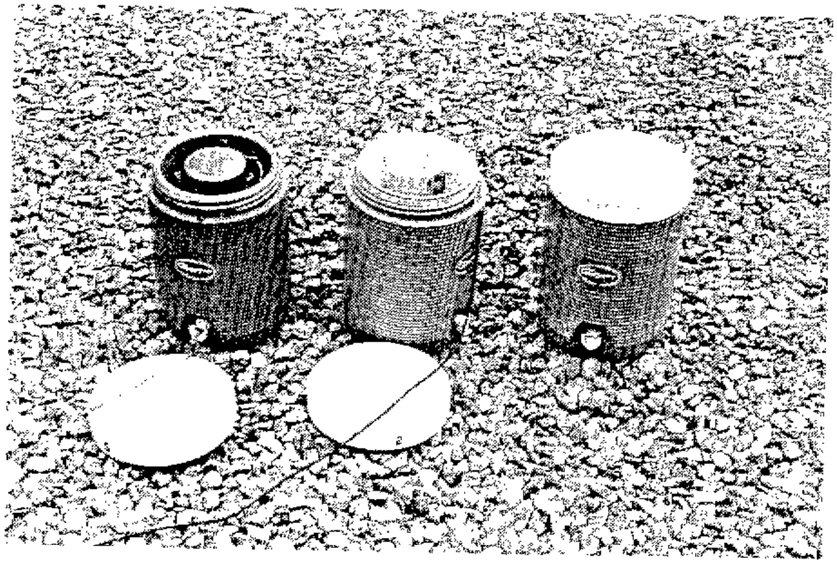

Figure 4.3.5.3 *Three mass containers: Hot, ambient, cold (right)*

The volumes and masses involved with this device are listed in Table 4.3.5.1. The air space between the inside of the 2-gallon container and the outside of the insulated bottle is filled with either a cylindrical structure with a heater strip and thermostat "floated" on stainless steel spacers (#3, hot), air (#2, ambient) or ice (#1, cold).

Table 4.3.5.1 - Details of a Solid Mass Thermal Device

Component	Volume (cm^3)	Mass (g)
Aluminum cylinder (less holes)	485	1,341
Holes	58	0.1
Air inside quart bottle	1,100	1.3
Quart bottle	931	1,154
Air outside quart bottle	5,882	7.1
2-gallon container	10,206	1,600
Total for #2 - ambient	18,662	4,104
Quart bottle (see above)	2,574	2,496.4
Ice-water mixture	4,706	4,706
Air above ice-water	1,176	1.4
2-gallon container	10,206	1,600
Total for #1 - cold	18,662	8,804
Typical Transducers:		
Minco S28F36Y nickel-iron	2.4	7
Rosemont RMT 78-39-7	5	36

The ratio of 1,341 grams of thermal mass to about 43 grams of sensors meets the design goal of a small sensor thermal impact. The several layers of insulation and the minimization of thermal conductivity paths meets the long time constant goal for the thermal mass.

A test was conducted to document the performance of the thermal mass assemblies and to show the time required to condition the hot and cold masses and the time constant of the ambient mass, see Figure 4.3.5.4. From the beginning of the test at a little after 10:00 a.m., when ice was put into #1 and the heater was plugged in for #3, it took about 9 hours for the slope to be flat enough to be confident that the mass had a homogeneous temperature. The maximum rate of change of the ambient mass was 0.01 °C/min. The stability of the measuring circuit is shown by the line with triangle symbol. The thermal conductivity of aluminum is 0.5 cal./sec through a plate one centimeter thick across an area of one square centimeter when the temperature difference is 1 °C. Steel is 0.1, rubber is 0.0005 and air is 0.00005 (Hodgman, 1955). The aluminum cylinder exchanges heat with its environment (except for the transducers being tested)

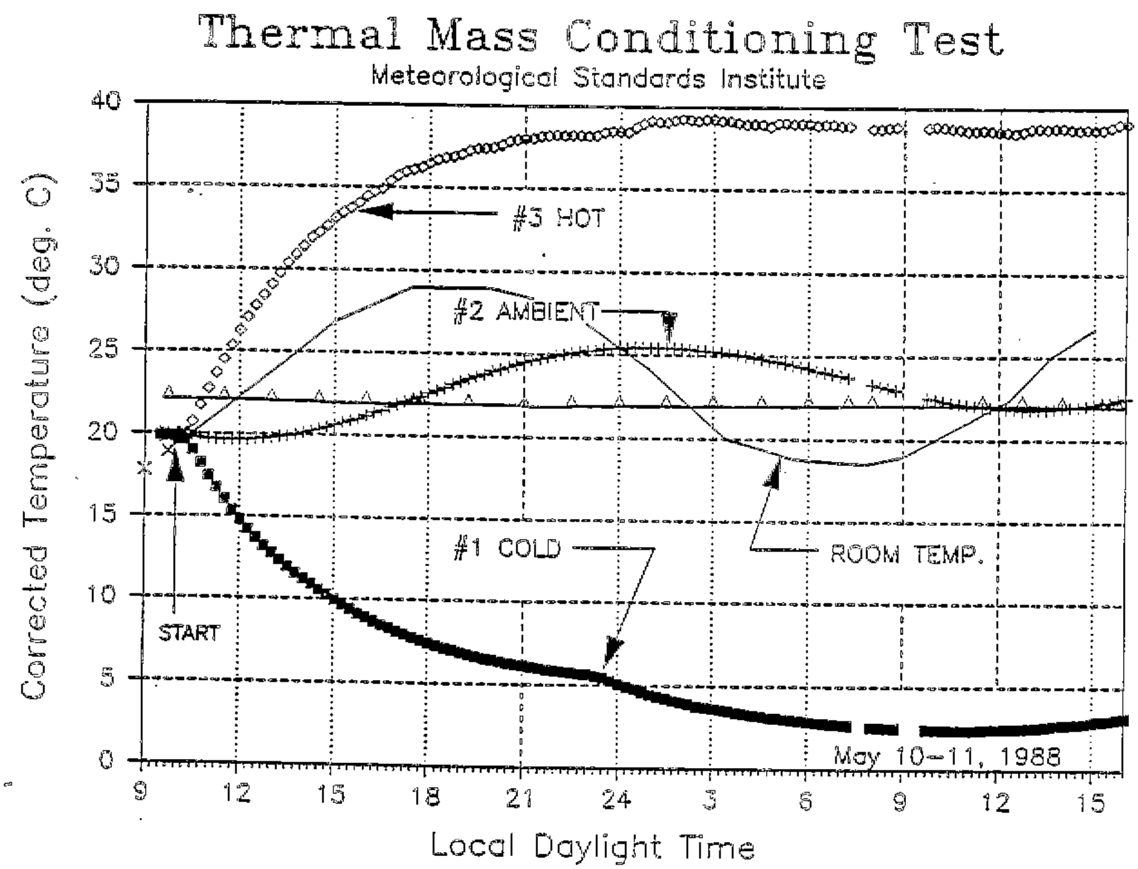

Figure 4.3.5.4 *Thermal mass conditioning and response test.*

through 450 cm^2 of air, 2.4 cm^2 of lucite and 0.1 cm^2 of steel. The difference in temperature between the holes where the transducers are mounted can be estimated from the difference in conductivity within the aluminum and within the environment outside the aluminum (99.5% air), or 10,000:1. If the mean temperature of the cylinder changes at 0.01 °C per minute, the gradient change between hole temperatures could be 0.000001 °C per minute.

Having created a stable environment, there needs to be an accurate method of measuring both the relative and absolute temperatures of the thermal masses. A three transducer data system was designed for this purpose. The report of its calibration is shown at the end of this section in 4.3.5.4.

4.3.5.2 Delta Temperature (ΔT)

Calibration of a ΔT system involves two parts. One is the matching of the transducers at zero difference and the other is the gain of the signal conditioner for a known difference in temperature of element resistance.

The first part involves placing the ΔT transducers together in a series of stable thermal masses. A stable thermal mass is any mass which is at least 25 times the mass of the sensors being conditioned by the thermal mass and which has thermal gradients of less than 0.01°C/cm throughout the mass. Start at cold, somewhere in the 0°C to 5°C range, and record the system ΔT output after stability has been reached in 30 to 60 minutes. Take readings about five minutes apart. When the readings stabilize, average the last five. Assume the output reports a difference of -0.02°C. Then move the two transducers to the thermal mass at ambient temperature, somewhere in the 15°C to 25°C range. When stability has nearly been reached, start taking readings about five minutes apart. When the readings have stabilized, average the last five readings. Assume the output reports a difference of +0.03°C. Finally, move the two transducers to the hot thermal mass, somewhere in the 35°C to 40°C range, and wait 30 to 60 minutes for stability to be reached. Take readings about five minutes apart. Assuming they are -0.09, -0.07, -0.05, -0.04, and -0.03, stability has not been reached. After another 30 to 60 minutes take another series of measurements about five minutes apart. Now they are -0.01, +0.01, 0.00, 0.00 and +0.01. Stability has been reached and the average of the last five readings, 0.00, is recorded.

This test has confirmed that the two sensors are matched to each other and to the generic transfer function with which the signal conditioning circuits have been set. It may be that the matching was done in the circuitry. It does not matter. It has been shown that the transducers and their parts of the circuitry agree with each other at three different temperatures. If agreement is not within ±0.05°C of the true value of 0.00°C, look to the manual or the manufacturer for guidance in correcting the problem. The ΔT system should start off with agreement in controlled conditions of much better than 0.1°C if the atmospheric measurements are to approach that accuracy. The methods described here for building a stable thermal environment and sampling the outputs for zero difference are only an example which works. The only important criteria is that it be documented in terms of stability, whatever method is used.

The second part of the ΔT calibration sets to tests the gain of the difference amplifier. Pick a common temperature for the site and substitute a fixed resistor for one transducer, arbitrarily choose the lower one. Assume the transducer is a 100Ω platinum type (see Table 4.3.1.1) and your resister is 108 ±1Ω. Substitute a precision decade box for the upper transducer. Adjust the decade box until the ΔT output is the voltage equivalent of 0.00°C. If the range is -5 to +15°C for a 0 to 1 volt output, 0.00°C is 0.250 volts. The output now reads 0.250 volts and the decade box reads 107.96Ω. If 107.79Ω represents 20°C, and if 0.389Ω represents a 1°C change (0.0389Ω for 0.1°C change or 0.01Ω = 0.0257°C), the simulated temperature for both transducers is (107.96 - 107.79 = 0.17; 17 x 0.0257 = 0.437) 20.437 ±0.026°C or between 20.41 and 20.46°C.

If the decade box is changed to 108.35 (107.96 + 0.389), the upper simulated transducer is now 1°C warmer than the lower simulated transducer. The output should read +1°C or 0.300 volts (1.000 volts ÷ 20 degrees = 0.050 volts/deg.; 0.250 + 0.050 = 0.300). If zero and full scale are to be challenged, set the decade box to 106.02 (107.96 - [5x0.389] = 106.02) for a 0.000 volt reading and set the decade box to 113.80 (107.96 + [15x0.389] = 113.80) for a 1.000 volt reading. Check the difference in box settings; 113.80 - 106.02 = 7.78Ω; 7.78 ÷ 0.389 = 20.00°C.

Beware of rounding errors if enough resolution is not carried or available on the decade box and the output. Check the decade box with a good ohm meter. Errors in the tens wheel (when switching from 106 to 113) may be larger than the smallest wheel. If the tens wheel is only good to 1%, the uncertainty is 0.10Ω or 0.26°C.

4.3.5.3 Temperature

The temperature calibration may be achieved concurrently with the ΔT calibration. Each thermal mass should have some accurate means of determining temperature. While the actual temperature is not important for the ΔT calibration, it should be recorded on the calibration form. If the temperature transducer is not one of the ΔT pair, it can be placed in a thermal mass at the same time the ΔT calibration is being done.

It may be that the system does not have a ΔT measurement but it does have a temperature measurement. Remembering that the temperature accuracy requirement is ±0.5°C, the temperature transducer can be challenged with a much simpler method. Liquid baths in a pint or quart insulated bottle with the transducer and a good ASTM or equivalent thermometer mixing the bath together will suffice. Be sure stability has been reached before taking the readings. Use care or parallax-avoiding devices when reading the thermometer.

4.3.5.4 Calibration Report Example

The following information is reproduced from a report prepared for Meteorological Standards Institute to document the accuracy of temperature instrumentation used on audits.

4.3.5.4.1 Introduction

During April 14 to May 8, 1988, a calibration program was conducted to verify the accuracy of three MINCO 604 ohm RTDs (resistance thermal devices). Three RTDs, Minco model S28F36Y labeled #1, #2 and #3, were originally calibrated in 1984 and have been in use for temperature and delta temperature auditing during the past four years. The earlier calibration was a relative calibration since the only accuracy of consequence to the application was the inter- relationship of the three RTDs. The current calibration is both relative and absolute.

4.3.5.4.2 The measurement circuitry

The three RTDs are connected in series to a battery powered constant current source of 0.500 mA. A fixed resistor (668 ohms) of low thermal sensitivity was also in the series loop as a reference source (REF). The voltages across each of the four resistors in the current loop were connected to input channels of an ADC-1 data logger. A NEC PC-8201A computer controlled the ADC-1 and collected the data. A program called ADCT was used to sample all the channels every 5 seconds and to record the average and standard deviation for periods of time selected through the program. Times of 10 minutes, 30 minutes and an hour were used at different times during the calibration. The ADC-1 provides an output in tens of millivolts. If the voltage across a 668 ohm resistor in a 0.0005 ampere current loop is 0.334 volts or 334 mV, the ADC-1 will output 3340.

4.3.5.4.3 The conversion of Minco ohms to temperature

In the Minco Application Aid No. 7, Table 14-604, the nominal values of resistance for temperatures are given. Nine sets of temperatures and resistances in five degree steps from 0°C to 40°C were used to find a mathematical expression for converting resistance to °C. A linear regression was not satisfactory. The quadratic solution to the regression analysis predicted the temperature at the nine points with an error of less than 0.01°C. Table 4.3.5.2 shows the input pairs, the predicted temperature and error, and the constants found and used.

Table 4.3.5.2 - Relationship of Minco Resistance to Temperature

y	x	$\hat{y}$	$\hat{y} - y$
---Minco Table	14-604---	predicted	
temperature	resistance	temperature	error
(°C)	(ohms)	(°C)	(°C)
0.000	604.00	0.006	0.006
5.000	617.98	4.998	-0.002
10.000	632.13	9.994	-0.006
15.000	646.46	14.996	-0.004
20.000	660.97	20.001	0.001
25.000	675.66	25.005	0.005
30.000	690.52	30.005	0.005
35.000	705.57	35.004	0.004
40.000	720.79	39.994	-0.006
for $y = a + bx + cx^2$		a = -269.1531523	
R = 1.00000009		b = 0.53213288	
n = 9		c = -0.00014322177	

A second step in the conversion requires the constant current to be exactly 0.5 mA so that the recorded voltage can be converted to temperature. The REF resistor is recorded as temperature using the generic conversion formula. The difference between the recorded value of REF and the correct value for 0.5 mA gives the correction. To find the correct value a series of measurements were made with the Fluke 8060A in the current loop. The least squares straight line was calculated for the data and both the data and the best-fit line are shown in Figure 4.3.5.5. The REF value for 0.5 mA was calculated and found to be 22.258 deg. C.

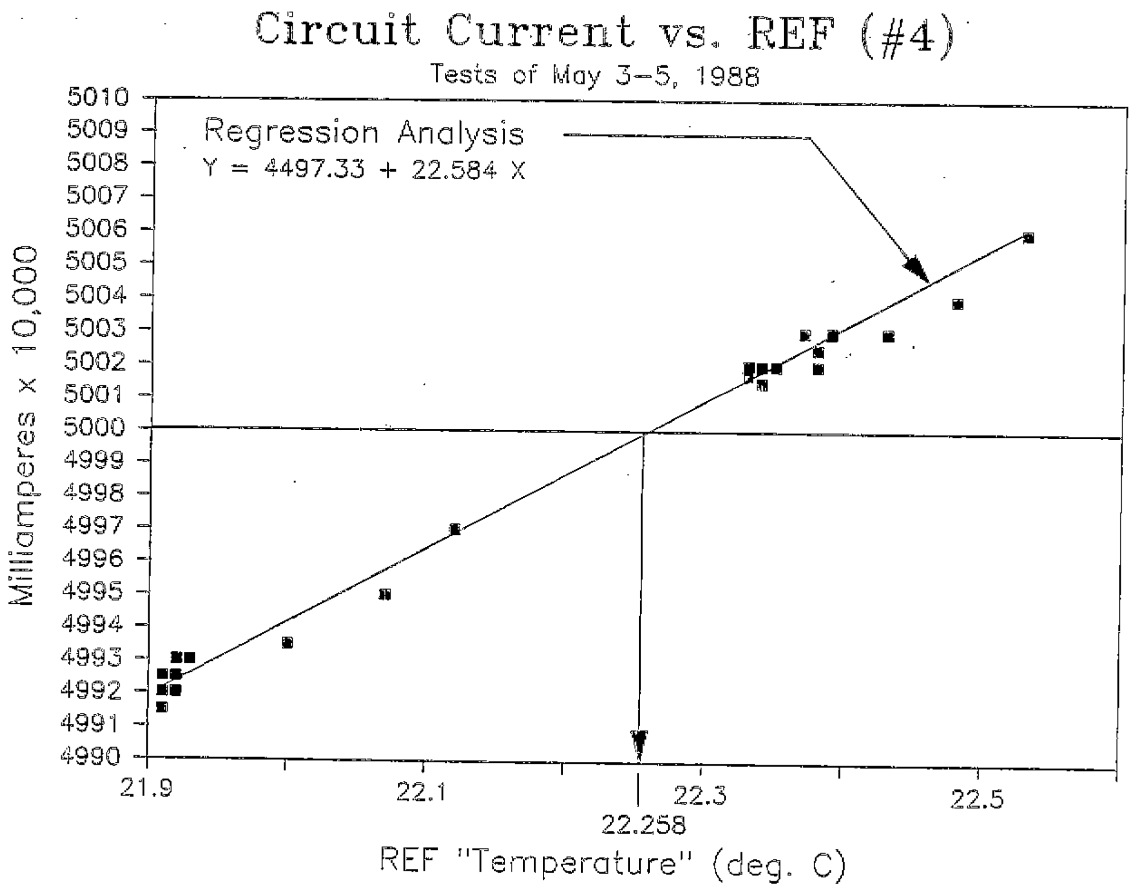

Figure 4.3.5.5 *"Constant" current versus REF resistor "temperature"*

The third step in converting the ADC voltage, V, to temperature, T, comes from the statement in the program ADCT which applies the quadratic equation to the resistance, assuming 0.5 mA current. That statement is as follows: $T = -269.15 + 0.10642V - 5.728E{-}06V^2$.

4.3.5.4.4 Measurement of true temperature

Two methods were used to find the true temperature. The first was the use of an ice slurry for 0°C. The second was the use of an ASTM 63F mercury-in-glass thermometer. The Princo Instruments Factory Certificate of Accuracy Tolerances for s/n 245453, scale range 18°F to 89°F with divisions every 0.2°F, states ±0.2°F or one division. The thermometer was read with an optical magnifier with anti-parallax targets to the nearest 0.05°F or about 0.03°C. In the relative sense, the temperature should be accurate to 0.1°C and in the absolute sense to 0.2°C.

4.3.5.4.5 The test facility

The three Minco RTDs were taped to the mercury bulb of the thermometer after all four devices were threaded through a rubber stopper. The assembly was submerged in an ice slurry or in water in a pint Thermos bottle (see Figure 4.3.5.5). The data logger signaled when an average was being recorded and the thermometer was read at the same time. The average from the Minco RTDs represents the middle of the time period while the thermometer was read at the end of the time period. A linear extrapolation of the Minco RTD data to the time of the reading of the thermometer provided comparable data.

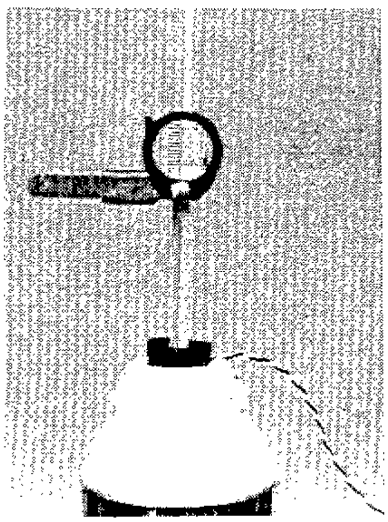

Figure 4.3.5.6
Calibration

4.3.5.4.6 Results

There were 73 thermometer readings over a nine day period covering a temperature range of 31.95°F to 89.05°F (-0.03°C to 31.69°C). The differences in temperature between Minco sensors #1 and #3, expressed in °C, and the thermometer temperature, expressed in °F, are shown in Figure 4.3.5.7. Sensor #2 was so close to #1 that it was not plotted. The calibration correction curves for all three sensors are shown on the figure. The best fit lines from the linear regression analyses are drawn on the figure. The coefficients are listed in Table 4.3.5.3.

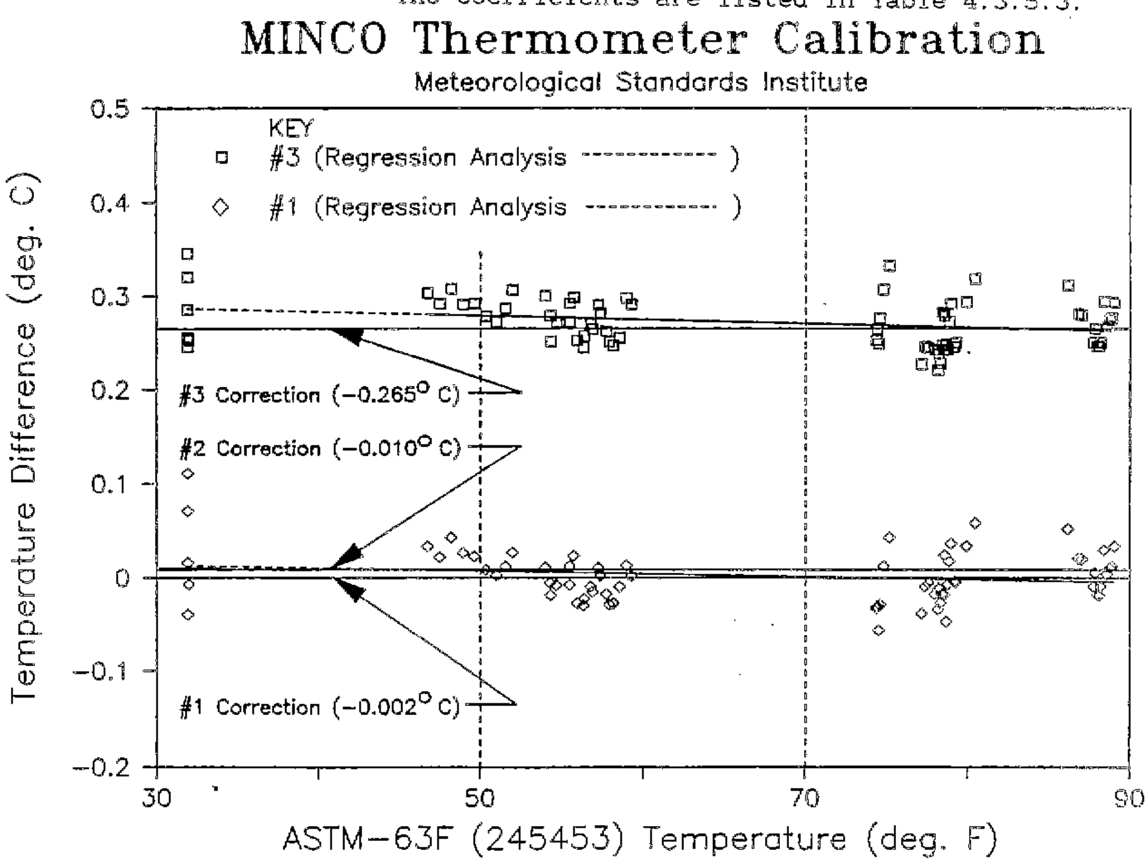

Figure 4.3.5.7 *Calibration of Minco sensors (RTDs)*

Table 4.3.5.3 Regression output for Minco #1 and #3 versus mercury-in-glass thermometer

	Minco #1	Minco #3
Constant (a)	0.02262	0.29951
Standard error of $\hat{y}$	0.02838	0.02534
Coefficient (b)	-0.00030705	-0.00041265
Standard error of b	0.00019593	0.00017491
Number (n)	73	73
Average difference	0.002	0.272
Standard deviation	0.028	0.025

The relative calibration, without consideration of an outside measurement of temperature, covered a range of 0°C to 44°C. There were 254 averages recorded for each of the Minco RTDs. The average and standard deviation of the differences between RTDs is shown in Table 4.3.5.4.

Table 4.3.5.4 Relative difference analysis

	---Minco Sensors (RTDs)---		
	#3 - #1	#3 - #2	#2 - #1
Average difference	0.2634	0.2753	0.0119
Standard deviation	0.0183	0.0165	

4.3.5.4.7 Conclusion

Using Minco #1 as a standard of comparison, and adjusting #1 for the bias of 0.002°C as shown in Table 4.3.5.3, the following accuracies of relative temperature are estimated.

Minco #1	#1 - 0.002 = temperature ±0.05°C
Minco #2	#2 + 0.010 = temperature ±0.05°C
Minco #3	#3 - 0.265 = temperature ±0.05°C

Similar tests in 1984 yielded the following corrections:

#1 + 0.00 = temperature
#2 + 0.03 = temperature
#3 - 0.22 = temperature

showing reasonable stability over four years and a reasonable capability to duplicate relative calibrations.

4.3.6 OPERATIONS, MAINTENANCE AND QC

4.3.6.1 Operations

From the standpoint of quality assurance, routine inspection of the temperature and ΔT data will help find problems soon after they occur. Routine inspection of the instrument system is also required. The temperature equipment is usually free from wear or change, except for the aspirated radiation shield, which tends to attract homeless critters of all kinds. Inspection of the temperature shield and transducer should be a part of the routine site visit and duly noted in the site log book. If there is no routine visit, a weekly or at the very least monthly visit is recommended. Systems usually have some built in calibration feature which substitutes resisters for the transducers to check or calibrate the signal conditioner. The site visit should include a temperature comparison with a simple hand-held thermometer for reasonableness. Guard against radiation errors with the hand held thermometer when working in direct sun light by keeping the thermometer in shade and away from body heat, including hot breath. The long time constant of mercury-in-glass thermometers (minutes) may make the inevitable warming from biasing heat difficult to observe.

4.3.6.2 Maintenance

Routine maintenance should include cleaning the aspirated radiation shield and verifying its function. This should not have to be done any more frequently than the bearing tests of the wind equipment. Since it is necessary to get the wind equipment down from the tower for the bearing tests, a cleaning of the radiation shields at the same time would be prudent and economical.

4.3.6.3 Quality Control

The best way to keep a ΔT system operating "in control" is to use a data quality control inspection for this variable. The QA Plan should supply the details of the ΔT inspection program.

An important aspect of the inspection is the background of the inspector. Ideally, an experienced QC meteorologist should be used. Lacking this resource, a training program should be made available to the person who will routinely perform the data inspections. The training will point out the nature of ΔT data as a function of wind speed, cloud cover, and time of day (solar angle).

Additionally, training will point out that a ΔT value, that is the difference between two well calibrated and shielded transducers, is just that. It is not a gradient measurement unless there is reason to believe that the air between the two transducers is reacting normally to thermal flux. Cases have been observed where a 10m to 60m ΔT averaged in excess of the auto convection rate for hours. The easy assumption is that there is an instrument error because autoconvection rates cannot be exceeded for long periods of time. The often unspoken assumption is that the ΔT transducers are in the same boundary layer and the difference in temperature represents the stability condition of the air. If the site can produce shallow or transitory surface boundary layers, as can happen with land-water interface regions, one transducer may be in one layer and the other transducer in the other layer. Then the ΔT value represents nothing more than single samples in different layers and lapse rate conclusions are invalid but the data are valid.

Training will show the normal diurnal cycle from a negative ΔT (lapse rate) in the daytime to a positive ΔT (inversion) at night (see Figure 4.3.2.1). An understanding of the physical process will support the data with other observations of weather conditions. The sun heats the surface much more than the air above it. The air at the surface is warmed by the now warmer surface. The warmer air expands and rises and mixes with the air it passes. This unstable convective process continues until the driving force, the surface warmer than the air above it, is neutralized. This can happen by either changes in the radiational heating of the surface or by the effective cooling of the surface through the heat removal process described above. Considering the strength of radiant heating (sun angle and sky cover) and the strength of the mixing process (wind speed), the size of the lapse rate (-ΔT) can be imagined.

Conversely at night, the surface is cooled by long-wave radiant loss to the cold universe. As the surface gets colder than the air above it that surface air is cooled by conduction. The cooled air is mixed by mechanical turbulence, caused by the wind flowing over surfaces elements, and slowly cools the air from the surface up. This very stable process results in the air above, not yet cooled, being warmer than the air below or an inversion (+ΔT). The size of the inversion results from the amount of surface cooling (sky cover) and the amount of turbulent mixing (wind speed and surface roughness). Calm clear nights will have larger inversions than cloudy and windy nights. If the wind is too high, there may not be an inversion at all. All the air may be mixed so well that there is no measurable difference between the two ΔT transducers.

To complicate the picture, temperature measurements also change as different air with different conditioning history is blown or advected past the measurement site. Diurnal rhythms can be seen as colder air flows down terrain features, such as hills and valleys, at night as a consequence of the kind of surface cooling described above. These vertically stable flow fields often become decoupled from each other. It is possible for one transducer to be in one stream of stable air while the other is in another stream. When this happens, the ΔT value may not represent a temperature gradient as much as two separate flow regimes, similar to the boundary layer example.

The trained inspector learns to see these processes in the ΔT data and to recognize physically unusual or unlikely data. If the data QC inspector looks at the data on a weekly schedule, problems will be uncovered shortly after they occur, thus avoiding long periods of data loss. One week is also short enough to allow memory of conditions to be correlated with the data. Discrepancy reports originated by the QC inspector can initiate the testing and corrective action, if necessary, by the instrument operator. If Δt measurements are taken, the purpose is usually the determination of stability categories or parameters for use in diffusion models. This important variable deserves careful attention and well documented evidence for validity claims. The accuracy of the measurement is achievable only with careful calibration. The accuracy of the data requires as much care given to data inspection between calibrations.

If only temperature is measured, the accuracy requirements are less difficult and the data QC inspection can be less rigorous. If data are collected, however, routine inspection is recommended and a weekly period is reasonable. The inspection compares the temperatures to reasonable values for the week and the nature of the temperature change to realistic patterns.

4.3.7 PERFORMANCE AUDIT METHODS

4.3.7.1 General Considerations

A performance audit is a measurement made by an independent method and person of the accuracy and precision of the performance of the measurement system. To make this determination for temperaturemeasurements, knowledge of the input conditions to the system sensors is required. It is also necessary to know what the system will do to these input conditions in producing an output. The output is simply the system output. Given the inputs and the transfer functions, the output can be predicted. The difference between the predicted output and the system output is the error of the system or its accuracy. The methodology starts with the ways of controlling and measuring the sensor inputs or knowing the inputs in an uncontrolled environment. Prediction of output from the controlled input requires knowledge of the transfer function but not necessarily its validity. Knowing the conditions of the uncontrolled environment does not require knowledge of any intermediate steps such as transfer functions. Temperature in is simply compared to temperature out. The method using the latter approach is called the Collocated Transfer Standard (CTS) method. The CTS method is seldom practical for ΔT. The best performance audit uses both methods where appropriate.

A performance audit must follow some written procedures. Since the procedures must be relevant to the design of the instrument or system being audited, only general principles will be described below with some specific examples. The data from the audit should essentially fill out an audit form. It is important, however, for the auditor to be sufficiently experienced to be able to deviate from the procedure or the form when the pursuit of truth leads away from the expected.

The starting point of an audit form is the documentation of the who, what, where, when, and how the audit values were acquired.

4.3.7.1.1 Who

The performance audit report form should contain a space to identify the auditor. The audit report which summarizes the audit findings should report the names and affiliations of the operators of the system.

4.3.7.1.2 What

The form should contain a section to identify the instrument being audited by manufacturer, model number, and serial number. Sub-assemblies, such as transducer or RTD and aspirated radiation shield, should be identified by number. If they are not numbered, the operator should be asked to mark them for identification.

The audit report should contain a list of all the equipment provided and used by the auditor, including model and serial numbers and time of last calibration, where relevant.

4.3.7.1.3 Where

The audit form should have a space to show the location of the sensor on a tower, including height. A sketch is useful to show the relative positions of the sensing elements with respect to possible biasing influences, such as the tower, other sensors and buildings.

4.3.7.1.4 When

The date or dates when the audit affected the system operation should be listed. The time when the system or a particular sensor was taken "off-line" and put back "on-line" should be listed. The time, or time period, when each data value was taken is vital for the comparison with the system output. Implicit in this is the need for the time the auditor uses to be correlated to the time the operator or the system uses. The auditor should rely on the National Bureau of Standards station WWV for correct time. Battery operated receivers, such as the Radio Shack Time Cube, are generally available.

4.3.7.1.5 How

The audit form should either contain a copy of the method used or reference the method number. The audit report should contain copies of the audit method used. The methods should be detailed enough to identify each step in the acquisition of the audit value and in the conversion of the value to units compatible with the system output. See Figures 4.3.7.1, 4.3.7.2, 4.3.7.4 and 4.3.7.5 for examples of forms and methods. These figures are intended as aids for writing specific methods and drawing the companion form. These may be reproduced if they are relevant.

4.3.7.2 Temperature Difference (ΔT)

4.3.7.2.1 Sensor control method

The audit method should simulate the most complete calibration method (see 4.3.5). The first step is to condition the thermal mass assemblies to be used to challenge the transducers to a zero difference environment. If stirred baths are to be used, be prepared to give ample time for equilibrium. The amount of time is not well predicted by the transducer time constant. Stability at the 0.01 °C resolution scale is desirable to back up claims of accuracy to 0.1 °C.

The transducers must be removed from the tower along with their cables. At some installations it will be difficult to impossible to remove the cables. Substitute cables may be used if care is taken to make sure the substitute does not change the output more than 0.01 °C. This should be verified by using a fixed resistance representing ambient temperature as a substitute transducer. Output readings using both the operational cable and the substitute cable should be recorded on the audit form.

The ΔT audit usually requires much more elapsed time than measurement time. It is practical to have equipment which allows the transducers to slowly reach their equilibrium state and to record this process through the entire system. This way the elapsed time can be used for the more labor intensive audit variables.

Temperature Difference - MSI method DLT006 (version 8/1/84)

This method provides for a measure of two temperature transducers with electric output used in a differential application, often called delta T. The audit equipment includes three thermal mass assemblies. Each is a cylinder of aluminum (6.4 cm diameter by 17 cm long, 1,341 g in 485 cc) with holes for different kinds of sensors. This 485 cc mass is suspended in the 1,100 cc inside volume of a stainless steel Thermos bottle, which is inside the 8500 cc inside volume of an 18,500 cc cylinder (Gott 2 gallon water cooler). The cold system is filled (4,500 cc) outside the Thermos bottle with a mixture of ice and water. The ambient system is full of ambient air. The hot system has a cylindrical frame spaced outside the Thermos bottle with a 600 watt strip heater operating through a 100 F thermostat. Conditioning for the hot and cold masses begins at least 12 hours before planned use. Each mass has a Minco 604 ohm (at 0 C) nickel-iron RTD. Resistance is measured and converted to temperature using a quadratic expression of the Minco Table 14-606 (see appendix). Relative corrections from intercomparisons made with the three RTDs in the same mass are applied yeilding relative accuracies of better than 0.05 C. Absolute accuracy is better than 0.5 C.

DLT006-A This method challenges the delta T pair at zero difference at three different temperatures. Place the pair of sensors in the hot mass. Record the mass temperature and the sensor temperatures (or the difference if that is all the signal conditioner provides) after about 40 minutes. Take two more samples five to ten minutes apart to verify stability. Move the pair of sensors to the ambient mass. Note: if DLT006-B is to be used, leave the hot mass unplugged and open to the air. Record data after 40 minutes and again in five to ten minute steps. Move the pair of sensors to the cold mass and record data after 40 minutes and again in five to ten minute steps.

DLT006-B This method challenges the delta T pair at a small temperature difference. The two masses to use are the ambient and the hot, after the hot has cooled down from use in DLT006-A or has been conditioned by a short input of heat. The true difference in temperature between the two masses should be between one and three degrees C. Install one sensor in the ambient mass (T 1) and one sensor in the "hot" mass (T 2). After 40 minutes record the temperatures of the two masses and the sensors or sensor difference if that is all that is available. Record the data again after five to ten minutes. The true difference will change slowly as the masses change temperature. Reverse the sensors and repeat the method waiting 40 minutes for the first data point. If the time constant of the segsor is observed to be fast enough to assure stability in less than 40 minutes, a shorter period may be used.

Figure 4.3.7.1 *Audit method for temperature difference*

PERFORMANCE AUDIT REPORT by ______________ DLT006

MEASUREMENT SYSTEM - Temperature difference
System number ____________________________________
Sensor ____________________________________
Transducers ____________________________________
Locations ____________________________________
Signal conditioner ________________________________
Data channels ____________________________________

DATE __/__/__ TIME off line _____ on line _____ test start ___

TRANSFER FUNCTION (volts per degree C) ________________
Conversion formula____________________

TEST RESULTS

DLT006-A

cold	sensor # mass		1_____ output		2_____ output		1-2 dif.	
time	ohms	degC	volt	degC	volt	degC	volt	degC
___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___
average								___

ambient	sensor # mass		1_____ output		2_____ output		1-2 dif.	
time	ohms	degC	volt	degC	volt	degC	volt	degC
___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___
average								___

hot	sensor # mass		1_____ output		2_____ output		1-2 dif.	
time	ohms	degC	volt	degC	volt	degC	volt	degC
___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___
average								___

DLT006-B

	T 1		T 2		A	T 1		T 2		B	B-A
sensor #	1_____ mass		2_____ mass		1-2 dif.	1_____ output		2_____ output		1-2 dif.	dif.
time	ohms	degC	ohms	degC	degC	volt	degC	volt	degC	degC	degC
___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___
average											___

	T 2		T 1		A	T 2		T 1		B	B-A
sensor #	1_____ mass		2_____ mass		1-2 dif.	1_____ output		2_____ output		1-2 dif.	dif.
time	ohms	degC	ohms	degC	degC	volt	degC	volt	degC	degC	degC
___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___
___	___	___	___	___	___	___	___	___	___	___	___
average											___

Figure 4.3.7.2 *Audit form for the temperature difference method*

The transducers are challenged with a known zero difference at three temperatures. This shows how well the transducers are matched and how well they follow the generic transfer function. The acquisition of these three data points may take four hours. Some judgment is required to identify the point at which stability is achieved. One clue is the reversal of a progression of data points. If, for example, the five minute average ΔT values are 0.09, 0.07, 0.06, 0.06, 0.05, 0.05, 0.06, 0.05, the last 0.06 can be taken as a signal that equilibrium has been reached. The reported value could be the average of five stable points (0.05) or the final stable value.

After the zero difference test has been completed, the gain of the difference circuit can be challenged by using the substitute resistance method. This method is described in 4.3.5. It is possible to use thermal masses at different temperatures, but it is not recommended because of the uncertainties of stability and four transducers measuring two temperatures to an accuracy of at least 0.025°C. Once the matching at zero difference has been established, the gain is adequately verified by normal electronic circuit procedures.

It is not practical to mount a second pair of sensors and aspirated radiation shields for collocated testing. The interference problems with the aspirators are hard to overcome. The physical problems associated with mounting parallel instruments are large compared to the value of the method. Considerable, but much less, effort is required for the Sensor Control method which provides numbers with acceptable confidence in their accuracy.

4.3.7.3 Temperature

4.3.7.3.1 Sensor control method

Usually the temperature transducer, if it is different from one of the ΔT pair, can be included in the thermal mass with the ΔT pair, or in another thermal mass at the same time as the ΔT pair is being tested. Timing for stability can include temperature with ΔT as though it were the same test. The big difference, however, is that the temperature transducer output is compared to the thermal mass transducer output as the audit value. A calibration of the thermal mass transducer is the key to the claim for accuracy given the challenged system.

If there is no ΔT system being audited, a simpler method is appropriate for the temperature system. A two point check using an ice slurry and an ambient bath is acceptable. Two insulated bottles (pint or quart size) with a cork to support a calibrated thermometer or a calibrated electric thermometer are required (see Fig. 4.3.5.6).Stability is easier to find since the readings are only taken to the nearest 0.1°C.

4.7.3.2 CTS Method

It is both practical and recommended to use the CTS method for temperature audits. The temperature transducer and its aspirated radiation shield (or even naturally aspirated shield) is usually located at an easily reached elevation. A CTS such as the Assmann Psychrometer shown in Fig. 4.3.7.3 can be located near the temperature sensor. It should be exposed so the wind reaches the CTS without bias error from other structures. If the wind during the audit is passing through a tower to reach the temperature sensor, the CTS should not be exposed to sample the same biased air temperature. The presumption is that the temperature sensor represents the air temperature. Any error from siting is a part of the measurement error. The CTS should be mounted to avoid all bias, if possible.

The CTS method should be used as an additional challenge to the temperature system. The two point Sensor Control method is a challenge to the transducer and signal conditioning circuit. The CTS method is a challenge to the radiation shield at one point on the range scale. A one point challenge of a temperature system provides no information about other temperatures. It may be that the operator calibrated the system at one point, perhaps the same ambient temperature as exists during the audit. There could be a slope error which causes large errors at near freezing. Having an accurate temperature measurement near freezing, accurate to 0.5°C, can be valuable as it relates to other sensors, such as wind. If the wind vane does not show any direction variation and the temperature system reports 0.0°C, there is a good chance that ice is on the direction vane bearing assembly. If the temperature system reports 3°C, with a 3°C error because only one point was used in calibration and audit, a different estimate of the direction vane problem is necessary. If audit or calibration records exist showing the full range performance of the temperature circuit, a one point spot check with a CTS is useful.

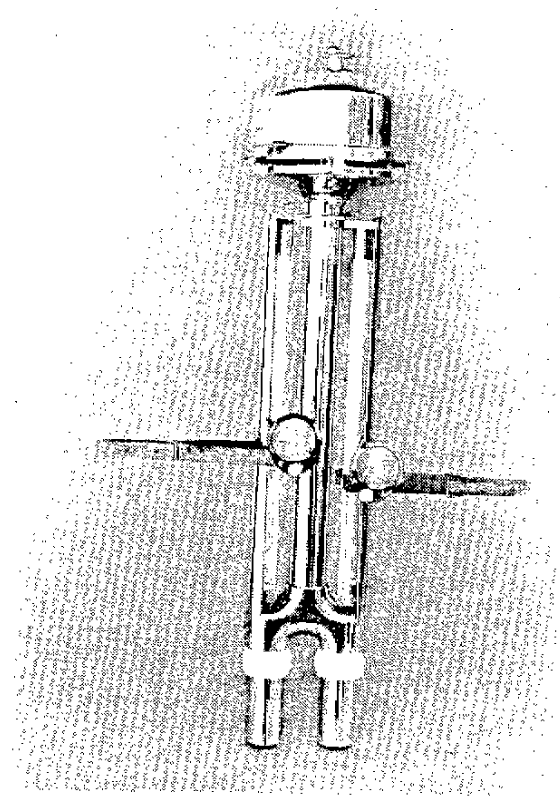

Figure 4.3.7.3
Assmann psychrometer

Temperature - MSI method TEM005 (version 8/1/84)

This method provides for a comparison of a temperature transducer with electric output to a calibrated transducer in a slowly changing thermal mass at three different temperatures. The audit equipment includes three thermal mass assemblies. Each is a cylinder of aluminum (6.4 cm diameter by 17 cm long, 1,341 g in 485 cc) with holes for different kinds of sensors. This 485 cc mass is suspended in the 1,100 cc inside volume of a stainless steel Thermos bottle, which is inside the 8500 cc inside volume of an 18,500 cc cylinder (Gott 2 gallon water cooler). The cold system is filled (4,500 cc) outside the Thermos bottle with a mixture of ice and water. The ambient system is full of ambient air. The hot system has a cylindrical frame spaced outside the Thermos bottle with a 600 watt strip heater operating through a 100 F thermostat. Conditioning for the hot and cold masses begins at least 12 hours before planned use. Each mass has a Minco 604 ohm (at 0 C) nickel-iron RTD. Resistance is measured and converted to temperature using a quadratic expression of the Minco Table 14-606 (see appendix). Relative corrections from intercomparisons made with the three RTDs in the same mass are applied yeilding relative accuracies of better than 0.05 C. Absolute accuracy is better than 0.5 C.

TEM005-A Insert the RTD being challenged in the cold mass. Wait about 30 minutes or until stable temperature is reached. Record samples of the RTD temperature from the system output. Record the resistance measurements of the mass RTD.

Move the RTD being challenged to the ambient mass and repeat the above procedure.

Move the RTD being challenged to the hot mass and repeat the above procedure.

TEM005-B Use an Assmann aspirated psychrometer mounted in the vacinity of the shielded temperature sensor. Wind the Assmann and let it run five minutes. Wind again and after an additional two minutes, begin reading the mercury-in-glass thermometers. Use the anti-parallax magnifiers. Record the temperatures from the Assmann and from the system taken at the same time. Be sure the two sensor systems are sampling from air which has not been biased by local mounting structures.

Figure 4.3.7.4 *Audit Method for Temperature*

PERFORMANCE AUDIT REPORT by ______________ TEM005

MEASUREMENT SYSTEM - Temperature

System number ______________________________
Sensor ______________________________
Transducer ______________________________
Location ______________________________
Signal conditioner ______________________________
Data channel ______________________________

DATE __/__/__ TIME off line ______ on line ______ test start ____

TRANSFER FUNCTION (volts per degree C) ____________________
Conversion formula______________________

TEST RESULTS

TEM005A

		cold						ambient			
		mass	output		dif.			mass	output		dif.
time	ohms	degC	volt	degC	degC	time	ohms	degC	volt	degC	degC
____	____	____	____	____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____	____	____	____	____
____	____	____	____	____	____	____	____	____	____	____	____
	average				____						____

		hot			
		mass	output		dif.
time	ohms	degC	volt	degC	degC
____	____	____	____	____	____
____	____	____	____	____	____
____	____	____	____	____	____
	average				____

TEM005B

time	Assmann			output		difference
	dry	wet	RH			
	degC	degC	%	volt	degC	degC
____	____	____	__	____	____	____
____	____	____	__	____	____	____
____	____	____	__	____	____	____

Figure 4.3.7.5 *Audit Form for the Temperature Method*

4.3.8 ESTIMATING ACCURACY AND PRECISION

Section 4.1.5 contains a detailed discussion of methods of estimating accuracy, precision and bias using wind speed and wind direction as examples.

Temperature transducers (as differentiated from temperature sensors which may include the radiation shielding) may be calibrated or audited by exposing them to a controlled environment such as a wet or dry thermal mass. The temperature of the mass is known either by an installed calibrated transducer or by collocating a calibrated transducer in the mass. The collocation alternative requires assurance that the mass is at a homogeneous temperature. The installed option requires assurance that the installed location is representative of the homogeneous mass temperature. When such a method is used, traditional statistical or metrological methods may be used to estimate accuracy. The precision of the method is the standard deviation about the series mean value of repeated measurements in the constant and controlled environment. Such methods are capable of achieving accuracies of 0.1 degree C and precision of 0.05 degree C or less.

When a collocated transfer standard (CTS) method is used, considerable care is required in stating the accuracy of the calibration or audit. The different exposures in the atmosphere of different transducers with different time constants in different radiation shields puts a larger uncertainty on the comparison than is found with a controlled environment. If, for example, a 2 meter temperature instrument is compared to an Assmann thermometer mounted nearby at the same height, the accuracy claim might be no better than the sum of the two different instrument accuracies. The accuracy of the method might be 1 degree C if each instrument is capable of a measurement accuracy of 0.5 degree C. There is reason to consider such a method as a comparative measurement rather than an audit or calibration.

It is possible that a CTS method can have greater accuracy. What is needed is a body of data which sets the functional precision of the CTS method by finding the best one can expect from collocated temperature instruments. A companion requirement is a body of data which compares different radiation shields as a function of radiation intensity, wind speed and wind direction relative to the orientation of the aspirator motor.

4.3.9 REFERENCES

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QUALITY ASSURANCE FOR PRECIPITATION MEASUREMENTS

4.4.0 INTRODUCTION

By definition, "The total amount of precipitation which reaches the ground in a stated period is expressed as the depth to which it would cover a horizontal projection of the earth's surface if there were no loss by evaporation or run-off and if any part of the precipitation falling as snow or ice were melted" (WMO, 1971). In any method of precipitation measurement, the aim should be to obtain a sample that is representative of the fall in the area. At the outset, it should be recognized that the extrapolation of precipitation amounts from a single location to represent an entire region is an assumption that is statistically questionable. A network of stations with a density suitable to the investigation is preferable.

4.4.1 TYPES OF INSTRUMENTS

Precipitation collectors are of two basic types: nonrecording and recording.

4.4.1.1 Nonrecording Gages

In its simplest form, a precipitation gage consists of a cylinder, such as a can with straight sides, closed at one end and open at the other. The depth of the liquid in the can can be measured with a measuring stick calibrated in subdivisions of centimeters or inches (Figure 4.4.1).

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

The automatic wet/dry precipitation collector, available in several designs, represents a specialized nonrecording instrument designed for programs involving the chemical and/or radioactive analysis of precipitation. The collector is built with a sensor that detects the onset and cessation of precipitation and automatically releases a lid to open and cover the collector. In one design, the lid can be made to remain open during either wet or dry periods. Another model is made with two collectors; the lid is made to cover one bucket during periods of rain and snow (Figure 4.4.2). In equipment of this kind involving precipitation chemistry, the volume of water in proportion to the constituents collected with the water is important, so evaporation must be kept to a minimum (see EPA, 1985).

4.4.1.2 Recording Gages

Recording gages are of two basic designs based on their operating principles: the weighing-type gage and the tipping bucket-type gage (Figure 4.4.3). The former, when made to NWS Specification No. 450.2201, is known as the Universal gage, indicating usage for both liquid and frozen precipitation. There are options for the remote transmission of signals from this type of gage. The standard National Weather Service Tipping Bucket Rain Gage is designed with a 12-inch collector funnel that directs the precipitation to a small outlet directly over two equal compartments, or buckets, which tilt in sequence with each 0.01 inches of rainfall. The motion of the buckets causes a mercury switch closure. Normally operated on 6 V d.c., the contact closure can be monitored on a visual counter and/or one of several recorders. The digital-type impulse can also be used with computer-compatible equipment.

Figure 4.4.1 *A typical non-recording Rain Gage (Belfort Instrument Co.)*

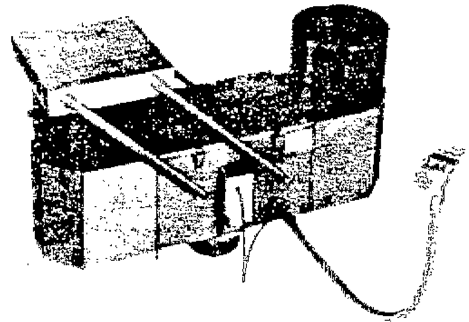

Figure 4.4.2 *Automatic wet/dry precipitation collector.*

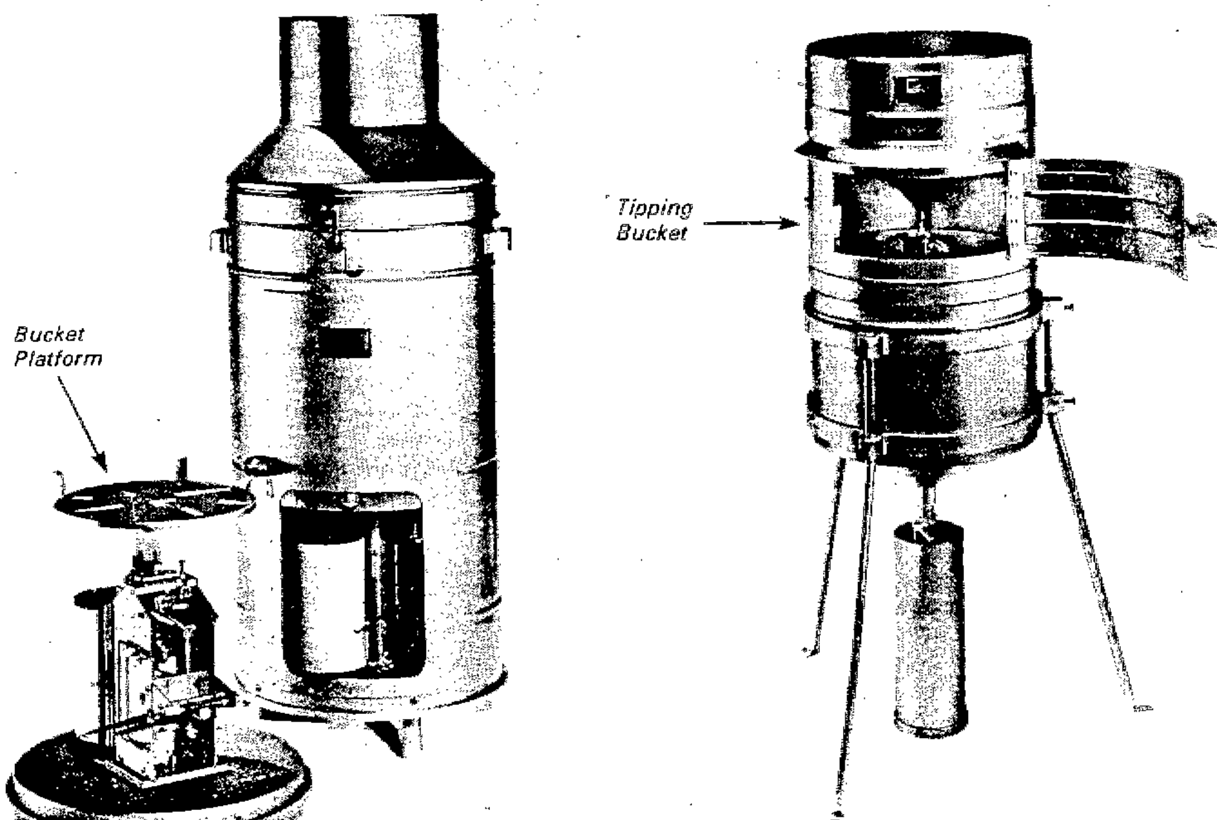

Figure 4.4.3 *A Typical Weighing Rain Gage (left) and Typical Tipping Bucket Rain Gage (Belfort Instrument Company).*

4.4.1.3 Instrument Characteristics

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

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

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

4.4.1.4 Accessories - Windshields and Heaters

Accuracy of measurement for all types of gages is influenced perhaps more by exposure than by variations in design. Windshields represent an essential accessory to improve the catch of precipitation, especially snow in windy conditions. The improved Alter design, made of 32 free-swinging but separated leaves supported 1/2 inch above the level of the gage collecting orifice, is an effective way to improve the catch. In a comparison of shielded and unshielded 8-inch gages, it has been shown that at a wind speed of 5 mph, the efficiency of the unshielded gage decreases by 25 percent, and at 10 mph, the efficiency of the gage decreases by 40 percent (Weiss, 1961).

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

4.4.2 SPECIFICATIONS

4.4.2.1 Precipitation Data Requirements

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

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

4.4.2.2 Procurement

In purchasing a suitable precipitation measuring system, specify the type that fits the data application and include a requirement for accuracy consistent with that application. A variety of gages are available commercially. In general, the standards established by NWS specifications result in the fewest problems. For example, there are numerous 8-inch gages available, but those following NWS specifications are made only of brass and copper, are more durable, and are reported to rupture less frequently under extended freezing conditions than those made of galvanized steel.

The procurement of a weighing type gage should include a tripod mounting base as well as a set of calibration weights. For locations that may not be readily accessible, or for locations with heavy precipitation, the bucket of the weighing gage should have an overflow tube. Refer to Section 4.4.3.2 for antifreeze specifications. If the resolution of time is not too important, recording rain gages of the drum type can be obtained with monthly rather than weekly mechanisms. Unless the tipping bucket gage is equipped with a heater, it is of no use for frozen precipitation.

4.4.2.3 Acceptance Testing

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

4.4.2.4 Calibration

Bench calibrations should follow the recommendation of the manufacturer. The electrical output gage or the drum recording gage measures weight, whether total weight in the case of the "weighing gage" or increments of weight in the case of the tipping bucket gage. Density of water is assumed so the weight can be expressed in units of volume or depth assuming the area of the collector opening. Calibrations of the measurement apparatus can be based upon the introduction of known volumes of water. The area of the collection surface must be known for the volume collected to be expressed as a depth. For example, an "eight inch" collector may feed a tipping bucket which tips when 7.95 cc of water has arrived. If this volume of water is to represent 0.01" of rainfall, the effective collection area must be 48.51 square inches, from the following calculations:

$$7.95 \text{ cc} = 0.485 \text{ in.}^3 = 0.01 \text{ in.} * 48.51 \text{ in.}^2$$

If the area is a circle, the diameter should be 7.86 inches.

$$(48.51/\pi)^{1/2} = 3.93 \text{ in. radius}$$

For rate-sensitive systems such as the tipping bucket, the rate of simulated precipitation should be kept less than one inch per hour. Calibrations require properly leveled weighing systems (gages) whether on the bench or in the field.

4.4.3 OPERATIONS

4.4.3.1 Installation

Refer to Section 4.0.4.4.2.4 which provides some siting guidance for precipitation measurement. The support, or base, of any gage must be firmly anchored, preferably on a level surface so that the sides of the gage are vertical and the collector is horizontal. The collector can be checked with a carpenter's level placed at two intersecting positions. The level of the bucket assembly on the tipping bucket gage is also critical and should also be checked along its length and width.

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

4.4.3.2 Field Operation of a Precipitation Measurement System

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

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

4.4.3.3 Preventive Maintenance

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

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

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

4.4.4 PERFORMANCE AUDIT METHODS

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

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

All types of precipitation gages should be measured to determine the effective collection area. This measurement is only required once but the difficulty of measuring the area of a slightly out-of-round collector may require several samples to accurately find the area.

4.4.5 REFERENCES

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QUALITY ASSURANCE FOR RELATIVE HUMIDITY OR DEW POINT TEMPERATURE

4.5.0 INTRODUCTION

Humidity is a general term for the water-vapor content of air. Other, more specific, terms for humidity include: absolute humidity, relative humidity, specific humidity, mixing ratio, and dew point (Huschke, 1959). This section discusses the measurement of relative humidity and dew point. Relative humidity (RH) is a dimensionless ratio of the actual vapor pressure of air to the saturation vapor pressure at a given dry bulb temperature. Dew point is the temperature to which air must be cooled, at constant pressure and constant water vapor content, to be saturated with respect to liquid water. Frost point is the temperature below 0°C at which air is saturated with respect to ice.

4.5.1 TYPES OF INSTRUMENTS

There are many ways to measure the water vapor content of the atmosphere. These can be classified in terms of the six physical principles (Middleton and Spilhaus, 1953) listed in Table 4.5.1. Examples of instruments for each technique are provided.

Table 4.5.1 Principles of Humidity Measurement

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

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

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

The temperature sensors in a sling psychrometer (Figure 4.5.1) are usually mercury- or alcohol-filled thermometers. The same is true of portable motor-operated psychrometers (Figure 4.3.7.3), but the psychrometric principle has been used with sensors made of thermocouples, wire-wound resistance thermometers, thermistors, and bimetal thermometers. Relative humidity and dew point are easily determined by observ- ing the difference between the dry bulb and the wet bulb--the wet bulb depression--and then referring to psychrometric tables, charts, or calculators. One must be certain to use computed values for the atmospheric pressure range of the location where the observation is taken.

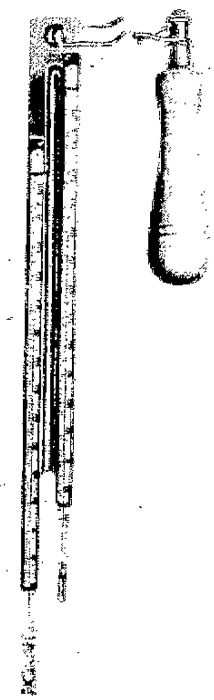

Figure 4.5.1 *Sling psychrometer*

More measurements of atmospheric water vapor have probably been made with the sling psychrometer than by any other manual method. When properly used and read, the technique can be reasonably accurate, but it is easily misused. The most important errors are from radiation, changes during reading, and parallax. The Assmann psychrometer continuously aspirates the thermometers and protects them from radiation which allows time and accessibility for a careful reading to avoid parallax (a parallax avoiding guide to keep the eye perpendicular to the meniscus is best, see Figure 4.5.2). For good accuracy, particularly where a variety of observers are taking measurements, an Assmann or equivalent type psychrometer is recommended. One should use the psychrometric tables with dew point values for the altitude (pressure) where measurements are being made.

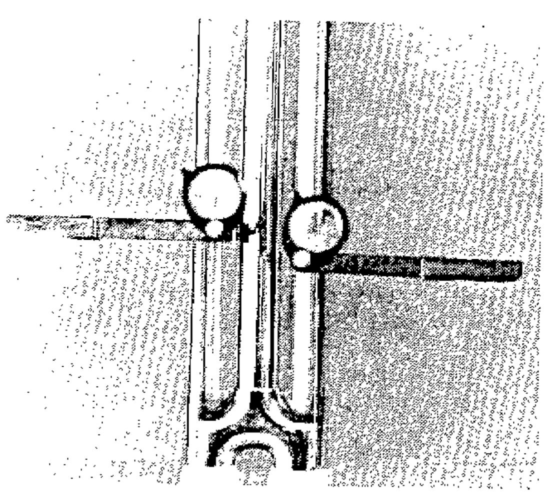

Figure 4.5.2 *Assmann psychrometer with parallax guides.*

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

Instruments that utilize the hygroscopic characteristics of human hair are used most frequently, primarily because of availability. The hygrograph provides a direct measure of relative humidity in a portable instrument that is uncomplicated and is relatively inexpensive. There are limitations in accuracy below 20 percent relative humidity and above 80 percent that may be unacceptable, as well as limitations for applications at low temperatures. Atmospheric Environment Services of Canada has found that Pernix, a specially treated and flattened hair element, can be used at temperatures below freezing without serious errors. The hygrothermograph made to an NWS specification incorporates human hair as the humidity sensor and bourdon tube (a curved capsule filled with alcohol) as the temperature sensor.

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

The dew cell, also known by the trade name Dew Probe, consists of bifilar wire electrodes wrapped around a woven glass cloth sleeve that covers a hollow tube or bobbin. The sleeve is impregnated with a lithium chloride solution (Figure 4.5.3). Low-voltage a.c. is supplied to the electrodes, which are not interconnected but depend on the conductivity of the atmospherically moistened lithium chloride for current flow. The temperature sensor in the tube is usually a resistance thermometer, but can be a thermistor, thermocouple, bimetal thermometer, capillary system, or any sensor calibrated for the proper temperature-to-dew-point relationship.

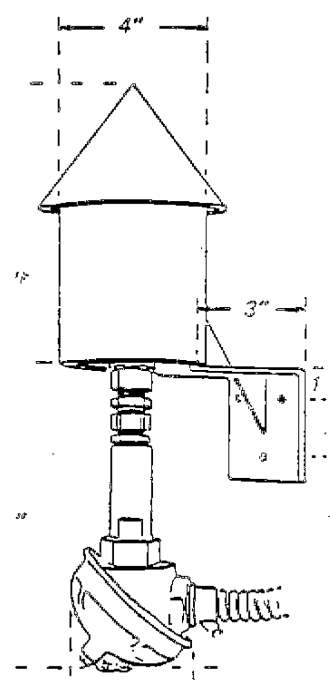

Figure 4.5.3 *A typical Dewcel sensor housing and transmitter*

In the early 1960's, the technique of detecting the dew point on a cooled mirror surface evolved into a production-type unit. This unit was automatically operated and had an optical dew-sensing system that incorporated thermoelectric cooling (Francisco and Beaubien, 1963). Four manufacturers now produce a meteorological type, thermoelectric, cooled-mirror dew point instrument (Mazzarella, 1977). Three of these instruments cover the range of -50 to +50 C. Linear thermistors are used to measure the mirror temperature in three of the units; a platinum wire sensor is used in the other. All are designed with simultaneous linear output signals for T_d (dew point temperature) and T (ambient temperature). Two of the manufacturers make claim to NBS-traceability with stated dew point accuracies ranging from ±0.2° to ±0.4°C and ambient temperature accuracies ranging from ±0.1° to ±0.5°C. All incorporate some form of standardization that involves clearing the mirror by heating, either automatically or manually. Although complex in design and operation, this type of cooled-mirror hygrometer is considered to be a functional standard.

In recent years, two other sensors for humidity have been used on tower installations for atmospheric pollution studies. One involves the use of an organic seed, cut and coupled to a strain gage. In principle, absorption of moisture in the seed results in distortion, which is converted to an electrical signal by the strain gage assembly. Reports on performance are mixed. Certainly the applications are limited, and the approach does not represent a technological advance. By contrast, the thin film capacitor, designed primarily for radiosonde applications, incorporates advanced technology (Suntola and Antson, 1973). Reports of users in the past have been mixed, with a common complaint of poor performance in polluted atmospheres. Modern capacitor-type sensors have achieved a better performance through improved design and user education.

4.5.1.1 Sensor Characteristics

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

It has long been recognized that there are some limitations in using the dew cell instrument (Acheson, 1963). The lowest relative humidity it can measure at a given temperature is the ratio of the vapor pressure of a saturated solution of LiCl to that of pure water. This is calculated to be 11.8 percent RH. A second limitation is that at -65.6°, -20.5°, +19.0°, and +94.0°C, LiCl in equilibrium with its saturated solution undergoes a phase change. Errors in dew point measurements occur at -69°, -39°, -12°, and +40°C. This problem is inherent in the use of LiCl and cannot be eliminated. It is estimated that the accuracy of the LiCl saturated salt technique is 1.5°C over the range of -30° to 30°C.

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

4.5.1.2 Sensor Housings and Shields

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

For meteorological applications, the dew cell element should be enclosed in a weatherhood to protect it from precipitation, wind, and radiation effects. This type of element functions best in still air. Some aspirated radiation shields are designed, in keeping with these specifications to house both a temperature sensor, which requires ventilation, and a dew cell, which requires only the smallest amount of air flow (Figure 4.5.4). The miniaturization of the dew cell has created some problems related to excessive air flow and solar radiation that remain only partially solved.

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

4.5.1.3 Data Requirements

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

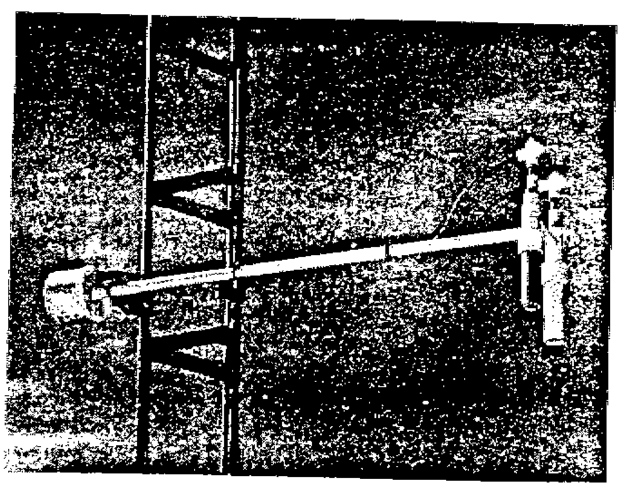

Figure 4.5.4 *A pair of tower-mounted Gill aspirated radiation shields for housing temperature and dew point sensors (Young).*

To calculate relative humidity (RH = 100 r, %) from air temperature (T, °C) and dew point temperature (T_D, °C), do the following:

$$r = \exp\left\{ a \left[\left(\frac{T_D}{b + T_D} \right) - \left(\frac{T}{b + T} \right) \right] \right\} \qquad (1)$$

where a = 17.27
b = 237.3

To calculate the dew point temperature (T_D, °C) from air temperature (T, °C) and relative humidity (RH = 100 r, %) use

$$T_D = \frac{b \left[\ln r + \frac{aT}{b + T} \right]}{a - \left[\ln r + \frac{aT}{b + T} \right]} \qquad (2)$$

To calculate relative humidity (RH = 100 r, %) from air temperature (T, °C), wet-bulb temperature (T_W, °C), and atmospheric pressure (P, mb) through the vapor pressure (e, mb) and the saturation vapor pressure (e_s, mb), do the following:

$$r = \frac{e}{e_s} = \frac{e_{sw} - AP\,(1 + BT_W)(T - T_W)}{e_o \exp\left[\frac{aT}{b + T}\right]} \qquad (3)$$

where $A = 6.6 \times 10^{-4}$
$B = 1.15 \times 10^{-3}$
$$e_{sw} = e_o \exp\left[\frac{aT_W}{b + T_W}\right]$$

To estimate wet-bulb temperature (T_W, °C) from air temperature (T, °C), dew point temperature (T_D, °C), relative humidity (r, ratio) and atmospheric pressure (P, mb), do the following:

$$T_W \cong T \left[\frac{P + T_D \left(19 + 130r - 28r^2 \right)}{P + T \left(19 + 130r - 28r^2 \right)} \right] \qquad (4)$$

The summarization of these relationships was suggested by A. L. Morris from material found in Z. *Geophysik*, **6**, **297**, 1930, the *Smithsonian Meteorological Tables, Sixth Revised Edition,* the *Glossary of Meteorology* and has been augmented by his own derivation of expression (4).

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

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

4.5.2 SPECIFICATIONS

4.5.2.1 Procurement

The selection of a humidity instrument is guided by the application to which the data will be put. The PSD (Prevention of Significant Deterioration) guideline (EPA, 1987) provides the following: "...If the permit granting authority determines that a significant potential exists for fog formation, icing, etc., due to effluents from the proposed facility, error in the selected measurement technique should not exceed an equivalent dewpoint temperature error of 0.5°C. Otherwise, errors in equivalent dew-point temperature should not exceed 1.5°C over a dewpoint range of -30°C to +30°C." This latter tolerance allows for the use of lithium chloride dew cells.

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

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

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

4.5.2.2 Acceptance Testing

Test at least the ambient atmosphere at one point in normal wind and radiation.

4.5.2.3 Calibration

The procedure for calibrating the thermometers in a psychrometer is essentially the same as any thermometer calibration (See Section 4.3.5).

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

4.5.3 OPERATIONS

4.5.3.1 Installation

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

4.5.3.2 Field Operation and Preventive Maintenance

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

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

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

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

4.5.4 PERFORMANCE AUDIT METHODS

Instrument audit procedures for hygrometry systems follow calibration procedures. A systems audit should be performed near the beginning of a field measurement program.

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

Given the qualifier that humidity is a very difficult measurement to make, a rule of thumb for judging the accuracy of a humidity monitoring system with an Assmann as the CTS is as follows: when the CTS and the challenged system agree in dew point temperature to within 1°C, the challenged system is assumed to be within 0.5°C of the true value. This arbitrarily assigns an uncertainty in dew point temperature of ±0.5°C for the Assmann which is true for most of the range.

Auditing is best backed by authoritative standards. ASTM, 1982, 1983, 1984 and 1985 may be of selective value.

4.5.5 REFERENCES

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QUALITY ASSURANCE FOR SOLAR RADIATION MEASUREMENTS

4.6.0 INTRODUCTION

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

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

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

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

Longwave radiation has a wavelength as follows:

Infrared (IR)	4 μm to 100 μm

and comes from the Earth and its atmosphere. The instruments most commonly used for environmental monitoring are discussed below.

4.6.1 TYPES OF INSTRUMENTS

4.6.1.1 Pyranometers

Pyranometers are instruments that measure the solar radiation received from the hemispherical part of the atmosphere it sees, including the total sun and sky shortwave radiation on a horizontal surface (Figure 4.6.1). Most pyranometers incorporate a thermopile as sensor. Some use a silicon photovoltaic cell as a sensor. The precision spectral pyranometer (PSP) is made by Eppley Laboratories and has two hemispherical domes designed to measure sun and sky radiation on a horizontal surface in defined wavelengths. This is achieved by substituting one of several

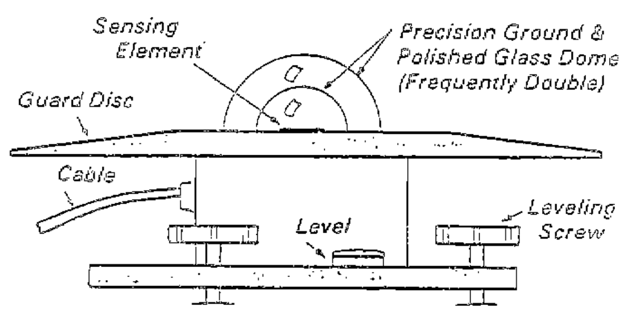

Figure 4.6.1 *Features of a typical pyranometer (Carter, et al., 1977)*

colored Schott glass filter domes for the clear glass outer dome. The smaller dome suppresses convection, so this type is better sited if tilted from the horizontal.

4.6.1.2 Bimetallic Recording Pyranometers

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

4.6.1.3 Net Radiometers

Net radiometers or net pyrradiometers are designed to measure the difference between downward and upward total radiation, including the total incoming shortwave and longwave radiation and the total outgoing shortwave and longwave radiation. There are two basic types of net radiometers. The ventilated plate type, often referred to by the name of the designers (Gier and Dunkle), is more popular in research applications than the type with hemispherical polyethylene domes originally designed by Funk. Both incorporate thermopiles with blackened surfaces. Because net radiometers produce a signal with a positive sign when the incoming radiation exceeds the outgoing, the recording equipment must be designed with an offset zero.

4.6.1.4 Sunshine Recorders

Sunshine recorders are designed to provide information on the hourly or daily duration of sunshine. Only one commercially available, off-the-shelf type of sunshine recorder is now available. This is the Campbell-Stokes design (Figure 4.6.2), designated as the interim reference sunshine recorder "IRSR" by the World Meteorological Organization. The device consists of a glass sphere 10 cm in diameter mounted in a spherical bowl. The sun's rays are focused on a card that absorbs radiation and changes color in the presence of sunlight. The recorder is used infrequently in the United States but extensively abroad, primarily for the collection of climatological data. The National Weather Service routinely uses a Sunshine Switch, which incorporates one shaded photocell and one exposed photocell.

Figure 4.6.2 *A Campbell-Stokes Sunshine Recorder (U.S. Army, 1975)*

4.6.1.5 Instrument Characteristics

Only the characteristics of pyranometers and net radiometers, the two types of instruments used most frequently in pollution-related programs, will be discussed in this section. The pyranometer is not to be confused with the pyrheliometer, "an instrument for measuring the intensity of direct solar radiation at normal incidence" (WMO, 1971). The pyrheliometer is mounted in a solar tracker, or equatorial mount, automatically pointing to the sun as it traverses from east to west (Figure 4.6.3). By contrast, the pyranometer is mounted facing toward the zenith. Ideally, the response of the thermopile sensor in the pyranometer is proportional to the cosine of the angle of the solar beam and is constant at all azimuth angles. This characteristic is known as the Lambert Cosine Response, an important characteristic of pyranometers. For the majority of applications related to atmospheric pollution, Class 2 and Class 3 are satisfactory (see Table 4.6.1).

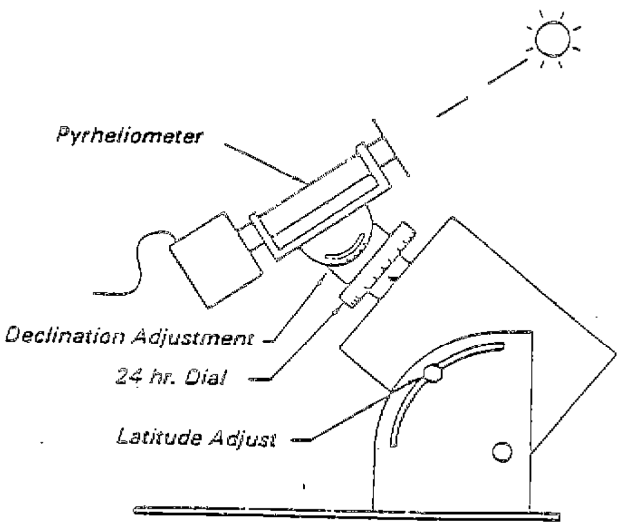

Figure 4.6.3 *Features of a typical pyrheliometer and tracking mount (Carter, et al., 1977)*

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

4.6.1.6 Recorders and Integrators for Pyranometers and Net Radiometers

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

4.6.2 SPECIFICATIONS

4.6.2.1 Procurement

In purchasing a solar radiation measurement system, follow the practice of matching the data requirements to the instrument selection, specifying the performance required on the purchase order (complete with test method to verify performance) and testing the performance in receiving. See Section 4.1.4.5 for comments on traceability protocol. Many types of radiation instruments have been developed, especially in recent years, because of an increasing interest in environmental considerations (Gates, 1962), meteorological research (Monteith, 1972), and solar energy (Carter, et al., 1977). Except for special studies, the requirements for relating radiation to stability can be satisfied by purchasing sensors of Class 2 or Class 3 as identified by the WMO (see Table 4.6.1).

Table 4.6.1 Classification of Pyranometers According to Physical Response Characteristics

	Sens. (mW/cm^2)	Temp. (%)	Lin. (%)	Max Time Constant (sec.)	Cosine Response (%)
1st Class	± 0.1	± 1	± 1	25	± 3.0
2nd Class	± 0.5	± 2	± 2	60	± 5.7
3rd Class	± 1.0	± 5	± 3	240	± 10

Class 2 sensors offer the advantage of providing data comparable to that collected at National Weather Service stations and at key locations of Department of Energy (DOE). The sensors to be specified should be commercially available, field proven by the manufacturer for several years, and have the technical requirements established by WMO standards. Several American Society for Testing and Materials (ASTM) standards are available (ASTM, 1984). When purchasing a recorder or integrator, one must match the calibration factor or sensitivity of the sensor to the readout equipment. It must be recognized that the signals from net radiometers, in contrast to pyranometers, require zero-offset capability to accommodate both negative and positive voltage outputs.

4.6.2.2 Acceptance Testing

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

4.6.2.3 Calibration

The user of a pyranometer or net radiometer is normally not equipped to calibrate the sensor. The best the user can do is to perform field calibration checks on two cloudless sky days. These checks involve a side-by-side comparison of the sensor to a sensor of similar design, the calibration of which can be traced to a transfer standard. Since 1975 all measurements have been made in accordance with the Absplute Radiation Scale or equivalently the World Radiometric Reference established at the International Pyrheliometric Comparison IV at Davos, Switzerland (NCAR, 1984, pp. 4-103). If a side-by-side comparison is not possible, the device should be returned to the manufacturer or to a laboratory with the facilities to check the calibration. The frequency of making comparative readings or having factory calibrations will depend on environmental conditions. Any indication of discoloration or peeling of a blackened surface or of scratches on the hemispheres of a pyranometer warrants recalibration and/or service.

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

4.6.3 OPERATIONS

4.6.3.1 Installation

The site selected for an upward-looking pyranometer should be free from any obstruction above the plane of the sensor and should be readily accessible for cleaning and maintenance. It should be located so that shadows will not be cast on the device, and away from light-colored walls or other objects likely to reflect sunlight. A flat roof is usually a good choice; but if such a site is not possible, a rigid stand with a horizontal surface some distance from buildings or other obstructions should be used. A site survey of the angular elevation above the plane of the radiometer surface should be made through 360 degrees (The Eppley Laboratory, Inc.).

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

Precautions must be taken to avoid subjecting radiometers to mechanical shock during installation. They should be installed securely and leveled using the circular spirit level attached to the instrument. Net radiometers are difficult to mount and to maintain free of vibration. Pyranometers of the Moll-Gorzynski design, used extensively by Atmospheric Environmental Sciences (AES) of Canada, are oriented so that the emerging leads face north (Figure 4.6.4). This minimizes solar heat on the electrical connections of an instrument that is not temperature compensated. The thermopiles of these instruments should be oriented so that the long side of the thermopile points east and west (Latimer, 1972). The cable used to connect the pyranometer to the readout device, recorder, or integrator should be between 16 and 20 gauge and made of shielded, waterproofed 2-conductor copper wire. The sensor, shield, and readout device should be connected to a common ground. Potentiometric millivolt recorders are to be used with most high-impedance, low-signal radiometers. Cable lengths of 300 m or more are practical. Galvanometric recorders can be used with silicon cell radiometers. Soldered, copper-to-copper junctions between instrument connectors and/or cables are essential. Pyranographs or actinographs should be installed on a level surface immune to shadows. These instruments should be placed in such a way that the sensitive bimetallic strips lie within 2 degrees of true east and west with the glass inspection window facing north (in the northern hemisphere).

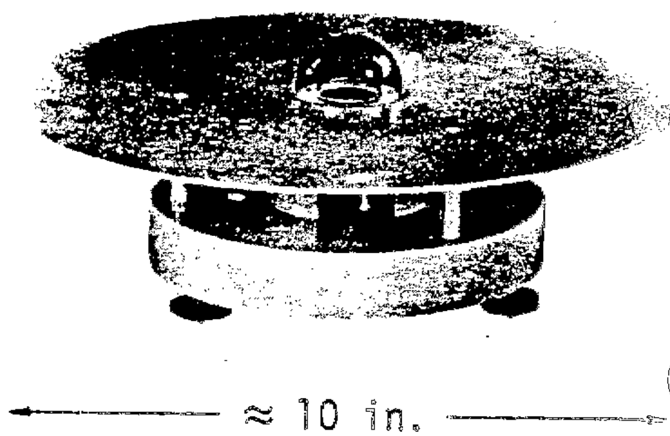

Figure 4.6.4 *A Moll-Gorczynskia Solarimeter (U.S. Army, 1975)*

4.6.3.2 Field Operation of a Solar Radiation System

As part of the quality assurance program, a field calibration check should be performed at least once every 6 months according to the procedures outlined in Section 4.6.2.3. Solar radiation instruments require almost daily attention. The data should be inspected for a reasonable diurnal pattern and the absence of dark counting. Where strip chart or digital printers are used, daily time checks are desirable. Data retrieval will depend upon program objectives; but even for climatological programs, data should be collected monthly. All operational activities during a site visit should be logged.

4.6.3.3 Preventive Maintenance

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

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

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

4.6.4 PERFORMANCE AUDIT METHODS

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

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QUALITY ASSURANCE FOR ATMOSPHERIC PRESSURE MEASUREMENTS

4.7.0 INTRODUCTION

Surface atmospheric pressure is not generally a required measurement to make for an air pollution meteorology application. A pressure value may be required for the calibration or interpreta- tion. Section 4.5.0 lists some formulas for converting wet- and dry- bulb temperatures to dew point temperature or relative humidity where a pressure value is required. In many of these applications, a standard atmosphere pressure for the station elevation will be good enough. For greater accuracy without measurement, the current altimeter setting from a nearby airport will provide an adjustment of the standard atmosphere to present conditions. If measurement is desired, the following may be helpful.

4.7.1 TYPES OF INSTRUMENTS

The two most common barometers are the aneroid barometer and the mercurial barometer. These must be read to get a measurement. Most electronic systems which include pressure as a variable use a sensor which has an aneroid pressure sensor. The motion of the sensor as a result of pressure changes may be detected by any number of methods. The latest and most accurate is a capacitor type.

The Fortin mercurial barometer is used by the National Weather Service as the official station pressure instrument. Portable precision aneroid barometers are used to make pressure measurements available at different work stations. A standard on the measurement of pressure (ASTM, 1977) provides methods for calibration and height corrections.

4.7.2 SPECIFICATIONS

Meteorologists are familiar with the units of pressure called millibars (mb). When SI units were adopted internationally, the Pascal (Pa) was chosen as the pressure unit. The hPa (hecto Pascal) is the common expression of pressure in the SI units because it is equivalent to millibars. One standard atmosphere at standard gravity is:

1013.25 mb or hPa
29.9213 in. Hg at 273.15 K
14.6959 lbf/in^2

Any practical application will be well served by a pressure measurement accuracy of about 10 hPa (≅ 1% or 100 m in elevation). The best accuracy one can expect to achieve in a monitoring application is about 0.5 hPa.

4.7.3 OPERATIONS

If maximum accuracy is the goal, care must be given to the exposure of the pressure sensor. The sensor is sensitive to both the atmospheric pressure (weight of the air above the station) and wind pressure. Errors from wind may be at most about ± 3 hPa under ordinary conditions.

4.7.4 PERFORMANCE AUDIT METHODS

The audit instrument can be as simple as an aneroid barometer (altimeter) which has been compared to a calibrated barometer. Figure 4.7.1 shows a pocket altimeter which will provide all the resolution and accuracy required by normal applications. The accuracy for this small instrument, when properly used, is 0.2 % or about 2 hPa.

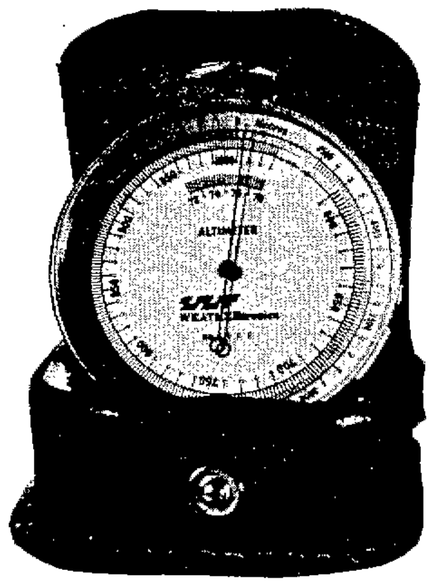

Figure 4.7.1 *Engineer's Altimeter (WEATHERtronics)*

4.7.5 REFERENCES

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QUALITY ASSURANCE FOR GROUND-BASED REMOTE SENSING DEVICES

4.8.0 OUTLINE AND SUMMARY

It has been common practice in air quality studies to use towers as platforms for meteorological monitoring. Such towers range in height from 10 to over 150 m and are typically outfitted with in situ sensors at several levels. Often, these towers fall short of the effective stack height (ESH) or the height of interest of an air quality study, and thus various techniques must be used to estimate meteorological conditions above the tower. Such techniques are not always the most realistic methods for estimating the vertical structure of the boundary layer. Tall towers are also expensive to install and maintain, and commonly, logistical constraints preclude proper siting of such a structure. Meteorological remote sensing provides an alternative to tower based measurements.

Over the past few years, developments in remote sensing technology have made it possible to obtain three-dimensional wind velocity (u, v, w) and virtual air temperature (T_v) profiles with the precision and accuracy suitable for regulatory applications. There are three types of commercially available remote sensors: SODAR (SOund Detection And Ranging) which uses acoustic pulses to measure horizontal and vertical wind profiles as well as the height above ground of the elevated inversion layer and mixed layer; radar (Radio Detection And Ranging) which uses electromagnetic (EM) pulses to measure horizontal and vertical winds; and radar/RASS (Radio Acoustic Sounding System) which uses both acoustic and EM waves to measure virtual air temperature, wind speed and wind direction profiles. Each will be described with detail in the following sections.

It is important that the user understand the fundamental differences between remote profiler measurements and in situ measurements. In situ sensors, including temperature probes, cup anemometers and wind vanes, are the mainstay of meteorological monitoring. They are found on towers, buildings, bridges or other structures and measure a particular meteorological variable by direct contact. However, by their very nature, these sensors disturb the environment in which they are sampling. These sensors are easily characterized in wind tunnels or environmental chambers and provide the user with a point estimate of the variable in question.

Meteorological remote sensing devices, on the other hand, provide measurements without disturbing the environment. In addition, remote sensing measurements are not restricted in height to the extent that in situ, tower-based measurements are. More importantly, data obtained from a remote sensor is represented as a spatial, or more specifically, a volume average. This particular characteristic of these data is described in later sections.

When comparing in situ sensors with profiling systems, we must acknowledge various tradeoffs between accuracy and the capability of characterizing the atmosphere. Conventional methods for obtaining upper air measurements have included aircraft, rockets, tetherballoons, and rawinsondes. Of these, rawinsondes released twice per day at some National Weather Service (NWS) stations have been the principal means for routine upper air observations. Rawinsondes provide point measurements of wind direction, wind speed, temperature, and dew point at intervals of about 100 meters. Morning and afternoon mixing heights are estimated from the twice daily vertical temperature profiles using the recommended standard method of Holzworth (1964; 1972). In this method, the mixing height is calculated as the height above ground of the intersection of dry adiabatic extension of the surface temperature with the vertical temperature profile. Various techniques are then used to interpolate hourly mixing heights between the two rawinsonde observations. This is not always a reliable method since the atmosphere can be extremely variable, especially on time scales of just a few hours. Remote sensors provide indications of the mixing height based on indications of the stable layer aloft, operate continuously and produce spatially averaged observations that are more capable of accurately characterizing the atmospheric boundary layer.

Remote sensors provide profile information based on time averaged observations that are fixed with height. Instantaneous values acquired by remote sensors may have errors associated with them due to random interference by sources such as bugs, birds or low flying aircraft. These erroneous values are removed by sophisticated algorithms and then averages are generated. These averages are usually computed for time periods of 15 minutes to one hour, depending upon the data requirements of a particular field study. These observations are also spatially averaged due to the large sample volume involved. This type of averaging over time and space characterizes the atmosphere more precisely than those values that are interpolated from a data set acquired by twice a day rawinsonde launches.

The following sections in this chapter describe the theory of operation of the various types of profiling systems that are commercially available, with an emphasis on system specifications. Sections follow on installation procedures and acceptance testing techniques to assure that acquired data are reliable and representative of atmospheric conditions. The inherent problems of calibration procedures and performance audits are discussed in detail. Standard operating procedures, maintenance schedules and quality control issues are outlined in the final sections.

4.8.1 TYPES OF INSTRUMENTS

Ground-based meteorological remote sensors have been designed to measure vertical profiles of wind velocity and virtual air temperature, as well as the height of the elevated inversion layer. The development and evolution of these devices over the last several decades have followed two similar but distinct paths: One based on acoustics and the other on electromagnetic (EM) radiation. Wind velocities acquired by sodar are based on the atmospheric effects on the propagation of acoustic energy, while radars are based on the atmospheric effects on the propagation of electromagnetic energy. Profiles of virtual air temperature are obtained by RASS which combines both acoustic and EM technologies. Table 4.8.1 provides a summary of typical specifications for the three major types of meteorological remote sensing devices. The theories of operation of all three profiling systems are discussed below.

4.8.1.1 SODAR

In the late 1960s and early 1970s, remote sensing techniques focused on the development of an acoustic-based wind profiling system, commonly known today as a sodar (e.g., Beran et al., 1971; Beran and Clifford, 1972; Beran, 1975; Balser et al., 1976; Kaimal and Haugen, 1975; Brown and Hall, 1978). The principle of operation is actually quite simple. The mono-static sodar consists of a transceiver antenna which is used to transmit and receive acoustic signals. The transducer generates a pulse of acoustic energy that is released into the atmosphere, either vertically or at some angle from the vertical. As the acoustic wave propagates upward, differences in atmospheric temperature and density cause some energy to be scattered back to the surface. This returned energy is received by the antenna and the frequency of the signal is determined. The difference between the transmitted and received frequencies, known as a Doppler shift, is directly proportional to the wind velocity along the beam axis.

The earliest sodars consisted of a single, vertically oriented, transceiver antenna approximately 1.5 m in diameter. The received signal intensity was recorded on facsimile paper. This system provided the user with qualitative information on the structure of the atmospheric boundary layer to heights of up to 1 Km. Since only one antenna was used to measure the vertical boundary layer structure, the system was termed as operating in a mono-static mode. In this configuration, sodar signals are scattered primarily by temperature gradients (Neff, 1988).

The next step of sodar development lead to a bi-static configuration which uses two antennas. One antenna acts as the transmitter and is tilted from the vertical, typically about 30°. The other antenna, which acts as a receiver, is situated away from but tilted toward the transmitting antenna. Bi-static sodars obtain wind velocity profiles by measuring the scattering of acoustic signals due to temperature and wind velocity fluctuations. Figure 4.8.1 depicts the mono-static and bi-static configurations.

Further refinement led to the development of three-beam and five-beam sodar systems. In a three-beam configuration, one antenna is pointed vertically and is used to measure the vertical wind velocity (w). Two other antennas, which are usually oriented off vertical and at right angles to each other, are used to estimate horizontal components (u and v) of the wind velocity. The five-beam configuration is similar to that of the three-beam, except that two additional antennas are used. These extra antennas are also oriented off vertical and are at right angles to each other. This configuration adds some redundancy, and in theory provides the user with a more reliable estimate of the horizontal and vertical wind velocity.

The phased array Doppler sodar is the latest design of an acoustic profiling system (Figure 4.8.2). An array of vertically pointing transceivers, in some instances horizontally with "bounce boards" to direct the beams to the vertical, is utilized. The number of transducers may range from 20 to over 100, depending upon the requirements of the system. These transducers are sequenced slightly out of phase to electronically "steer" the acoustic beam away from the vertical, thereby obtaining information required to estimate the horizontal wind velocity.

The horizontal components of the wind velocity are measured by releasing two acoustic signals into the atmosphere at an angle, typically 15° to 30°, off the vertical axis. The two acoustic signals are typically oriented at right angles to one another. One is usually directed toward the East or West so that the u component of the horizontal wind velocity can be determined while the other is directed toward the North or South for the v component. Figure 4.8.3 depicts this beam configuration. The mean horizontal and vertical wind velocity components can be approximated using the following simplified equations:

$$\bar{u} = \frac{V_r - w \sin\phi}{\cos\alpha \ \cos\phi} \tag{1}$$

$$\bar{w} = \frac{V_{rw}}{\cos\phi} \tag{2}$$

where V_r is the measured radial wind velocity (m s^{-1}) for the u axis, V_{rw} is the radial velocity in the vertical, ϕ is the elevation angle of the transmitted beam (degrees), and α is the azimuth angle (degrees). Normally in calculating the mean wind, time averaging is used to eliminate the effect of variations in the vertical velocity. Some systems correct for mean vertical wind if other than 0 m s^{-1}. This is useful in situations where the average vertical wind may not be zero (i.e., in complex terrain).

Sodars typically operate at frequencies from below 1 KHz to just over 4 KHz with typical power outputs in the range of 2 to 300 W. In operating or purchasing a sodar for a particular application, one should note that the lower the frequency and the higher the power output, the greater the range of the sodar. Therefore, sodars can be tuned to obtain the most sound information for a particular application.

The vertical range of a typical sodar is 0.5 to 1.5 Km and is a function of frequency, power output, and atmospheric stability. The most important factor affecting range is the presence of atmospheric turbulence, especially eddies on the scale of 0.1 to 0.3 m since these are the major source of reflectivity for acoustic waves. Range resolution is the distance between reported heights and is typically between 25 and 50 m. In a typical configuration about 20 to 30 levels are reported.

A mini phased-array sodar (mini-sodar) is a downsized version of its standard counterpart and has a height coverage of about 200 m and a range resolution between 5 and 20 m. The mini-sodar provides measurements near the surface and is useful for studying local flows and shallow inversions. Figure 4.8.4 shows a photograph of a mini-phased array sodar.

Sodar signals are shaped somewhat like a cone as shown in figure 4.8.5. The half-power beam width typically ranges from 2° to 10° depending on frequency and the size of the antenna aperture. The sampling volume increases with height and can be approximated by:

$$Sample\ Volume\ (m^3) = \pi L (h \tan \alpha)^2 \quad (3)$$

where L is the length of the transmitted pulse (m), α is the beam half width (degrees), and h is the height of the sample volume (m). For example, if the transmitted pulse length is 20 m, the beam half width is 2° and the height of interest is 500 m, then the sample volume would be near 19,000 m^3.

4.8.1.2 RADAR

The principles behind the Doppler radar are similar to sodar except radars use electromagnetic (EM) waves to sense turbulent fluctuations in the atmosphere. Because EM signals do not attenuate (dissipate) as quickly as sound waves, radars have greater vertical range than sodar.

The original Doppler radars operated at frequencies that required fairly large reflectors (i.e., water vapor, bugs, or chaff) to reflect the EM signal back to the receiving antenna. In the 1980s, radars were developed which used small scale wind and temperature fluctuations as the source of reflection of EM signals (Ye et. al., 1993 and Brown and Hall, 1978). These so called "clear air" radars provided a means to acquire winds aloft without the requirement for large diameter scattering mechanisms. Doppler radars today operate at a typical frequency of 915 MHz, and are capable of measuring winds to around 3 Km with range resolutions ranging from 60 to 400 m. Typical configurations designed for atmospheric boundary layer studies are capable of measuring to 3 Km with a vertical range resolution of 60 to 200 m, thus allowing about 20 to 30 levels to be reported. The lowest measurement height (minimum range) is typically between 150 and 200 m. The most important factor effecting the range is the presence of gradients in the refractive index of the atmosphere. Figures 4.8.3 and 4.8.5 provide a graphical representation of typical Doppler radar.

Doppler radars emit pulses of EM energy into the atmosphere. As the EM waves propagate outward, some energy is reflected back to the surface due to the presence of atmospheric density gradients and variations in the refractive index. The most common source of variation in the refractive index is the presence of humidity gradients. High humidity in the boundary layer provides an ideal environment for the radar to reflect its signal. In general, the more humid the atmosphere, the better the data capture efficiency and greater the range.

To determine the three-dimensional wind velocity, three independent EM signals must be collected and analyzed. A burst of EM energy is released in the vertical to derive the vertical wind velocity. Two other separate EM bursts, released at angles from the vertical, are required to determine the two horizontal wind components. In the past, three separate antennas were used to derive the three components of wind. One antenna pointed vertically and two other antennas tilted 15° to 30° off vertical and normally at an angle of 90° from one another. New phased array radars are now being manufactured which use one antenna for determining the three components of wind. The phased array system has the capability to electronically "steer" the energy pulse away from vertical, thereby providing the off axis information required to determine the horizontal wind components.

The transmitted half-power beam width of radar is larger than that of the sodar, ranging from 7° to 10°. Equation 4.8.2 may also be used to estimate the size of the sample volume for radar. For example, if the transmitted pulse-length is 60 m, the beam half width is 4° and the height of interest is 500 m, then the sample volume is nearly 230,000 m^3.

4.8.1.3 RASS

A Radio Acoustic Sounding System (RASS) is a combination of sodar and radar technology and is used to obtain profiles of virtual air temperature (T_v), along with the radar's wind profiles (see Figure 4.8.6). Virtual temperature is the temperature dry air must have to equal the density of moist air at the same pressure (Stull, 1988). An acoustic source is added to a Doppler radar, or a sodar added to a bistatic radar, and used as a reflective source for back scattering the EM signal. The variations in temperature produced by the compression and expansion phases of the acoustic wave provides a refractive index structure from which EM waves can scatter (Gaynor et al., 1993; Neff, 1988).

The RASS transmits an acoustic pulse vertically into the atmosphere followed by an EM pulse. Note that some RASS systems use continuous acoustic transmissions to provide the radar with a well defined reflective source. Since the EM wave travels much faster than the acoustic wave, the latter signal intercepts the former, and some EM signal is reflected back to the surface. The returned EM signal is analyzed to determine the speed of the acoustic pulse, derived from the Doppler shifted EM signal. The acoustic wave travels at the speed of sound, since this is a function of the ratio of specific heats, pressure and density of the air mass, it becomes a relatively simple exercise to derive an estimate for the virtual air temperature. The minimum recording height and range resolution of the temperature measurement are the same as radar, however the height coverage is similar to that of a sodar, typically 1 Km.

Table 4.8.1
Typical Specifications for Meteorological Remote Sensors

System	Variables	Frequency	Height	Resolution
mini-Sodar	u, v, w	3 - 4 KHz	< 0.3 Km	5 - 20 m
Sodar	u, v, w, z_i	1 - 3 KHz	< 2 Km	20 - 50 m
Radar	u, v, w	915 MHz	< 4 Km	60 - 200 m
RASS	T_v	2 KHz	< 1 Km	60 - 200 m

Note: u, v, w are the three components of wind, z_i is the height of the elevated inversion layer, and T_v is virtual air temperature.

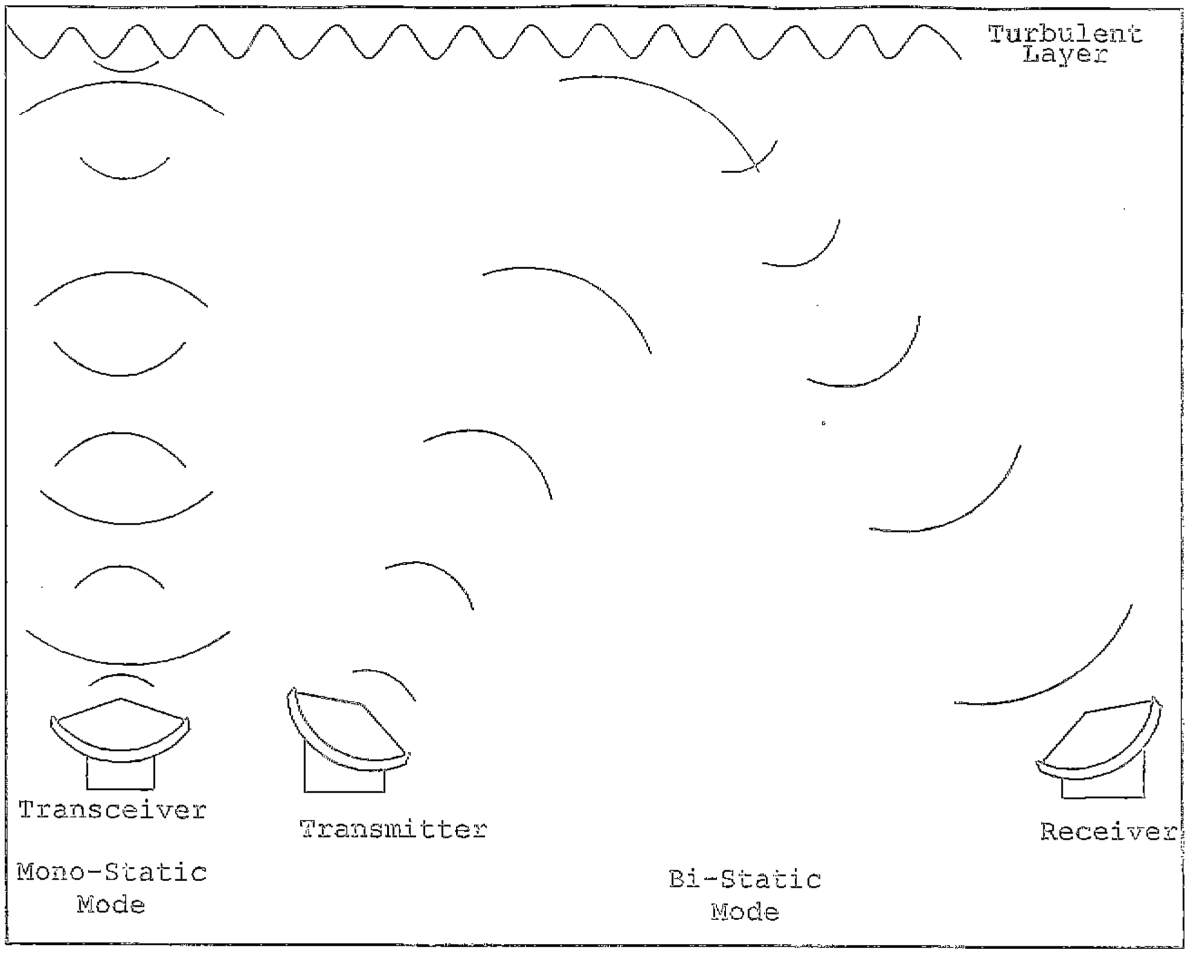

Figure 4.8.1 Depiction of a mono-static and bi-static sodar.

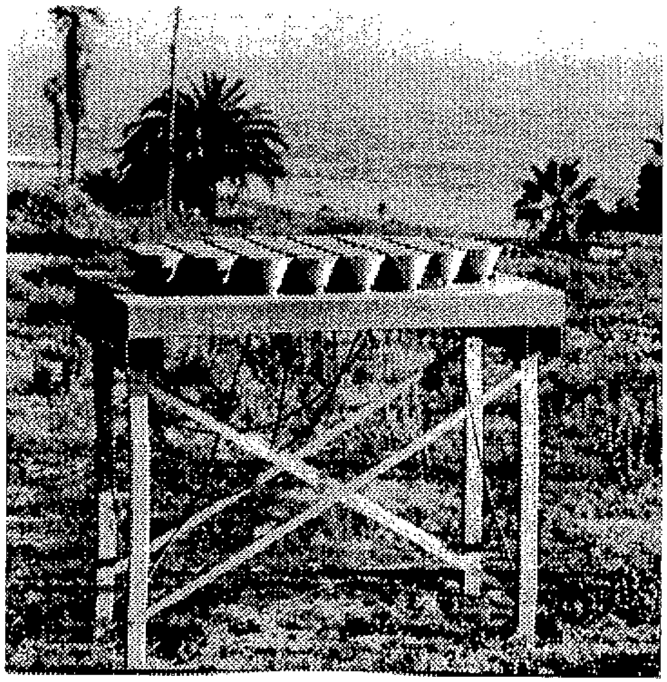

Figure 4.8.2 Photograph of a phased array sodar (Courtesy of Remtech, Inc.),

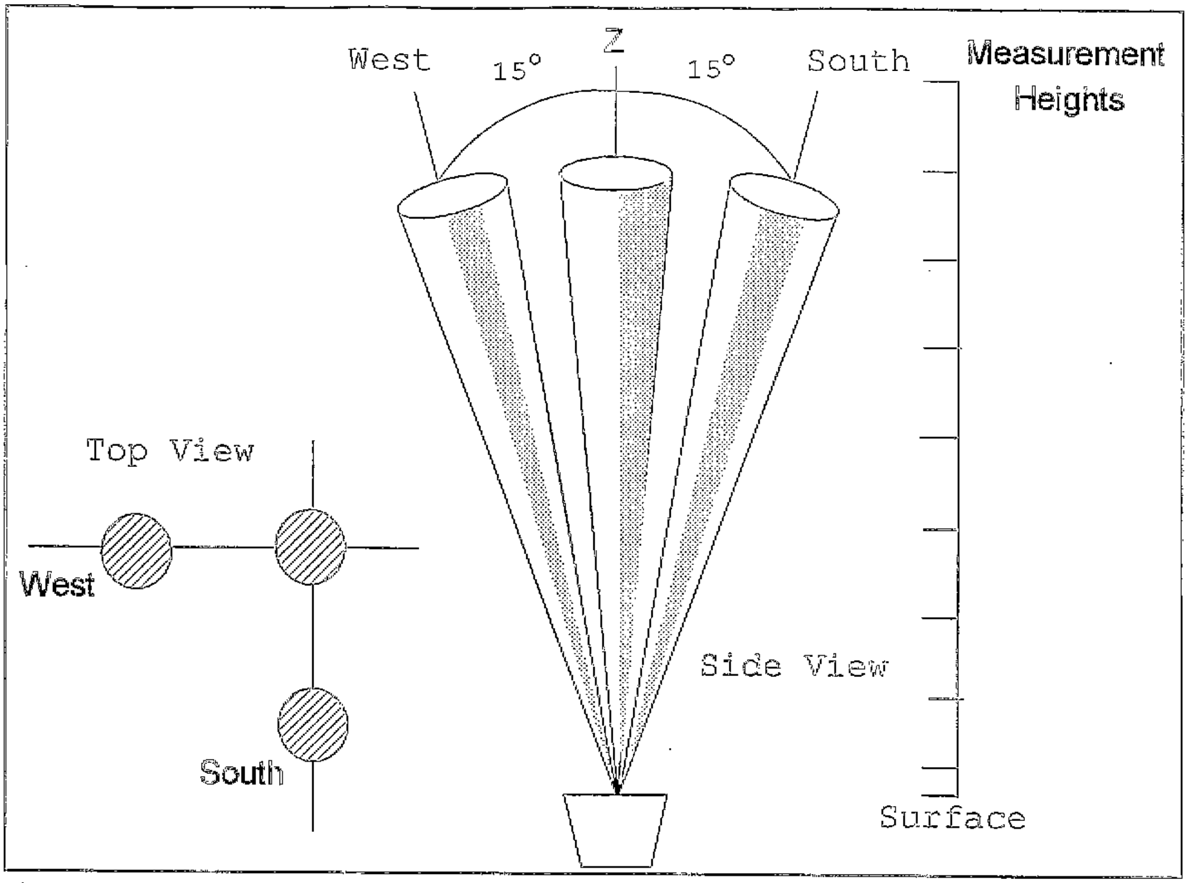

Figure 4.8.3 Typical beam configuration for a phased array sodar and radar.

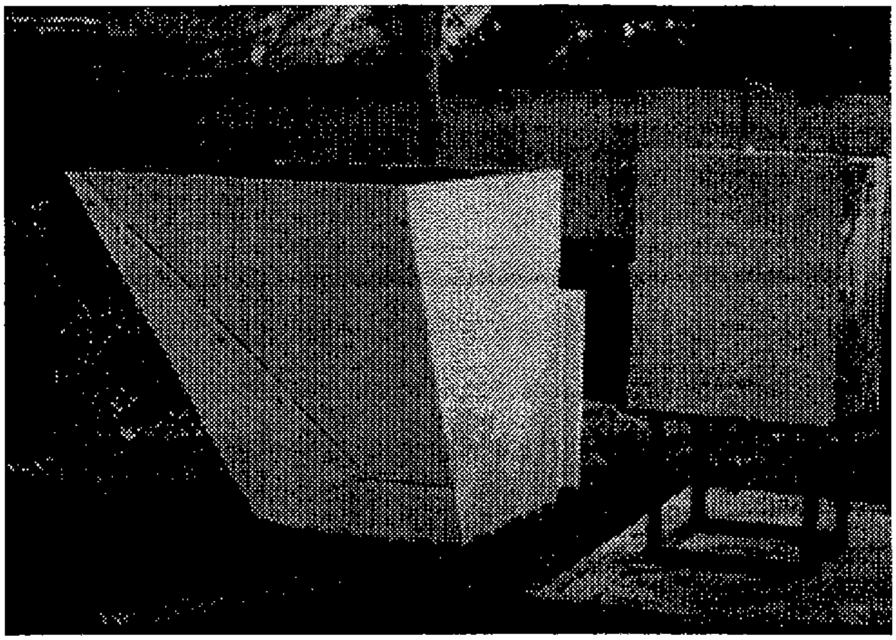

Figure 4.8.4 Photograph of a phased array mini-sodar (Courtesy of AeroVironment, Inc.).

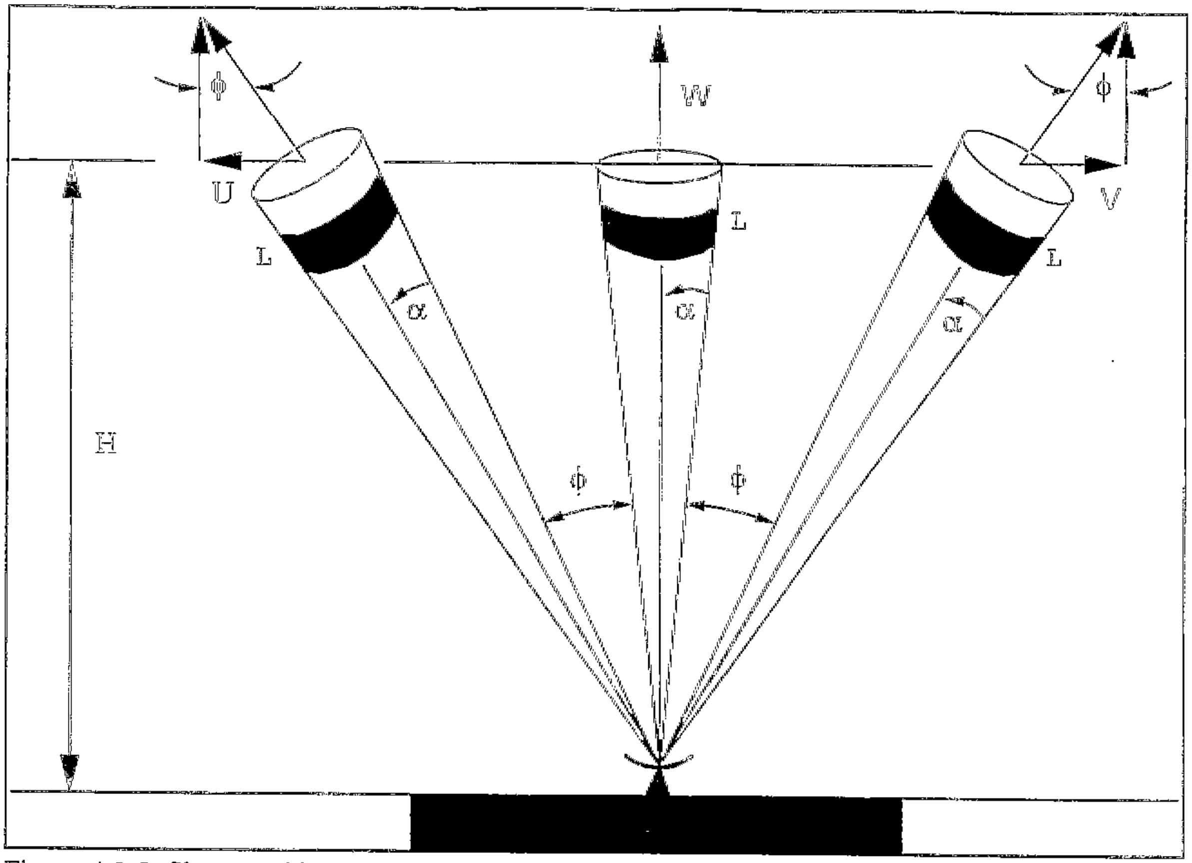

Figure 4.8.5 Shape and important components of a sodar and radar beam.

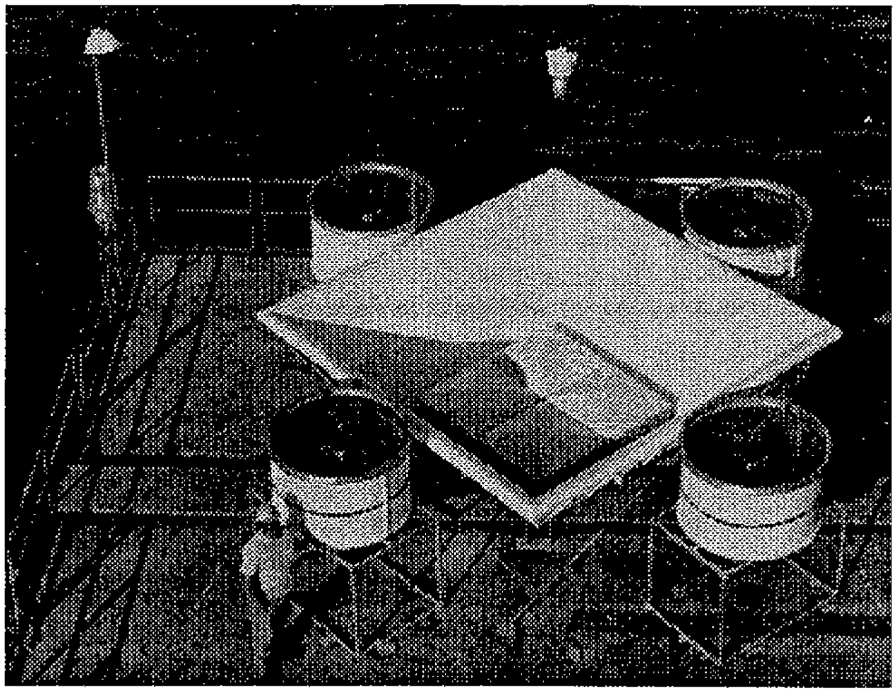

Figure 4.8.6 Photograph of a radar wind profiler with RASS (Courtesy of Radian Corp.).

4.8.2 SPECIFICATIONS

The previous section described the basics of remote sensing devices for meteorological monitoring. Meteorological remote sensing devices, by their very nature, must be configured to obtain the most reliable data possible for a given field site. Configuration may include modification of the profiler output signal frequency, output signal power, averaging intervals or sampling heights. The overall accuracy of an acquired data base is dependent, in part, on the surrounding terrain, nearby buildings, atmospheric stability, noise sources, insects and birds. When compiling a set of specifications for the purchase of a remote sensing device, it is important to determine site specific information that will aid the manufacturer in configuring the device to fit the user's needs. The following sections describe site specific parameters which need to be identified and provide some initial estimates of expected accuracy, precision and data capture efficiency.

4.8.2.1 SODAR

The specification for vertical range will normally determine the appropriate operating frequency. For example, if a user only requires low level winds (< 200 m), then a higher frequency (3 to 4 KHz) may be used. High frequency signals emit little energy in their side lobes and have a narrower beam width, thus producing a relatively small sample volume, see Figure 4.8.7. Although this provides a relatively cleaner signal, it does have a drawback. High frequency signals attenuate faster in the atmosphere then low frequencies. Therefore, more power is required to obtain the same vertical range. In situations requiring winds above 200 m, lower signal frequencies (1 to 3 KHz) should be used. Since low frequencies attenuate more slowly in the atmosphere, less energy is required to observe high level winds. The drawbacks with low frequency beams are that they emit more energy in their side lobes and have a wider beam width, thereby producing a larger sample volume with an increased possibility of generating false echoes.

Sodar signals are shaped somewhat like a cone as shown in Figure 4.8.5. The beam width typically ranges from 2° to 15° depending on frequency. The sampling volume increases with height and can be approximated by Equation 3.

Sodars are not usually configured for measurement of the structure of the elevated inversion layer above 1.5 Km, due to the enormous power requirements needed to probe the atmosphere to these heights. For regulatory modeling, atmospheric dispersion models used to derive pollutant concentrations and the site climatology will usually dictate whether inversion heights above 1.5 Km are required. If the user does not require wind velocity information above 1.5 Km, then a sodar configured with a low frequency and high output power should be adequate. Note that radar should be considered if wind profiles are needed above 1 Km.

Sodar options usually include software subroutines that perform a variety of QA/QC functions. It is important to purchase QA/QC software which provides an extra level of data validation. Care should be taken however, so as not to filter out any valid meteorological data. Inversion height routines are required if estimates of this level are to be reported. Software is also available for estimating the vertical and horizontal turbulence parameters, σ_w and σ_θ. However, care must be taken with how these values are generated since they usually have large errors associated with them and therefore, are not recommended for use in regulatory applications at this time. If they are used, great care must be taken to ensure that these values are accurate and meaningful. An effort is currently underway to investigate the suitability of using sodar derived σ_w and σ_θ estimates in regulatory modeling applications.

Some manufacturers provide routines to correct the horizontal winds for vertical velocity. In near flat terrain this is usually not a problem unless the system is not perfectly level. However, in complex terrain the average vertical wind velocity may be large and should be used to correct the horizontal winds, if the desired output is the total vector wind speed. During the acceptance test, discussed later, the wind speed from the sodar should be calculated in the same manner as the test instrument. During actual monitoring, the operator needs to be careful to supply the wind expected by the model (i.e., vector or scaler). For example, if a uvw anemometer attached to a tower is being used, then both the sodar and the uvw anemometer derived winds should be corrected for the mean vertical velocity if other than 0.0 ms^{-1}. Information concerning this correction may be found in most model documentation.

Gaynor et al. (1992) and Finkelstein et al. (1986) have determined the accuracy of wind speed estimates generated by sodars to be about 0.2 m s^{-1}, for atmospheric conditions experienced during the field studies. Sodar observations compared with tower-based measurements indicate the accuracy ranged from -1.04 to 0.44 m s^{-1} while the precision ranged from 0.6 to 1.7 m s^{-1}. These studies also concluded that the accuracy of the wind direction is about -3.0°, ranging from -6.8° to 4.0°. The reported precision ranged from 18.4° to 37.6°.

Unlike the data from in situ instruments, the quality of data from a sodar is a function of atmospheric conditions. When turbulence is low, the signal-to-noise ratio is low and it becomes increasingly difficult to determine the frequency shift of a return echo. When wind speeds are low, small errors in the horizontal velocity components can lead to large errors in the estimate of wind direction. The variability in the estimates of wind speed is also partially based on the inhomogeneities within the sample volume. For each sample height, the return frequencies are plotted and analyzed for a peak frequency, which is used to determine the Doppler shift. The estimated Doppler shift is then used to determine the average velocity within the sample volume. When the winds are inhomogeneous in the sample volume, the peak in the frequency plot becomes broad, and thus determination of the peak frequency becomes difficult. The error in determining the peak becomes an error in accuracy when compared with the true wind. The problem is compounded when determining wind direction. Wind directions are calculated using the u and v velocity information obtained from the off vertical sodar beams. The errors associated with determining the u and v velocities are accumulated and transferred when computing wind direction.

Inversion height calculations, in some systems, are based upon the calculations of σ_w and σ_θ. Other systems use profiles of reflectivity to estimate the inversion height. In these systems, sophisticated pattern recognition algorithms are used to determine the height of the inversion layer.

They are also capable of detecting multiple layers, if they exist.

Data recovery of sodars is highly variable and is dependant on atmospheric conditions at the various sampling heights. With sodars, it is common to have several levels of invalid or missing data. This is typically due to a lack of turbulence at those levels. It is up to the data analyst to interpolate or extrapolate missing wind data from the sodar output information. Weber and Wuertz (1991) describe a computer program that can be used to validate and fill in these missing data. However, care should be exercised so as not to smooth over any real data. Sodars typically have good height coverage during daytime hours when there is strong mixing and there is sufficient turbulence to provide an adequate reflective source. However, turbulence above the inversion layer may be suppressed sufficiently to inhibit data capture. In this case, no data would be recorded. This situation occurs frequently at night when the inversion height is below the maximum recording height of the sodar. Typical data capture ranges from about 50% to near 90% and is highly variable from hour to hour. Data capture here is defined as the percent of valid data received from the sodar during one averaging period divided by the total number of levels which the sodar is programmed to sample.

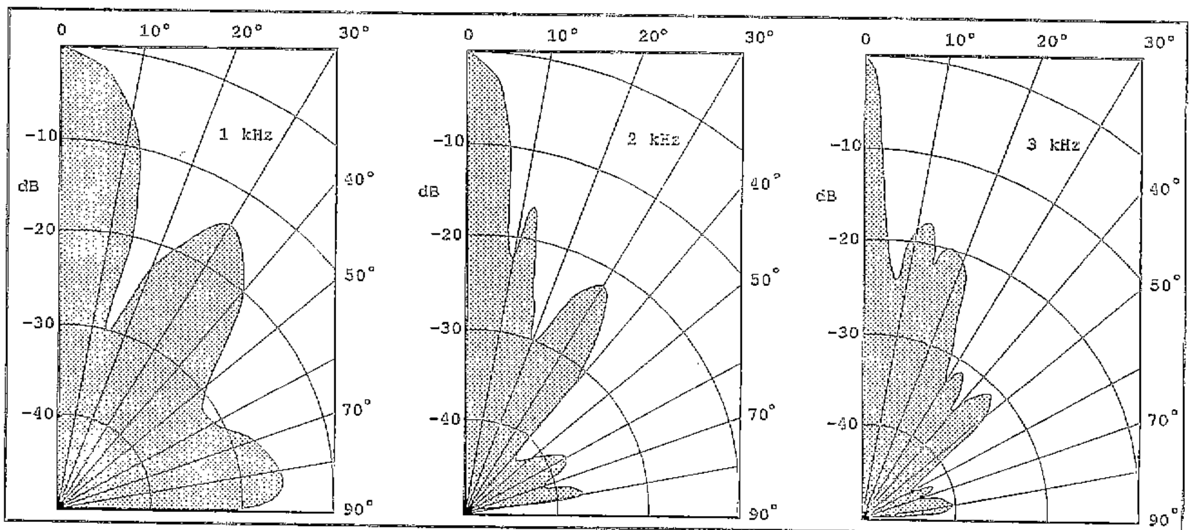

Figure 4.8.7 Sodar beam widths at acoustic frequencies of 1, 2 and 3 KHz with no acoustic absorbers (Neff, 1988).

4.8.2.2 RADAR

Radars are capable of measuring winds to several kilometers with a vertical resolution between 60 and 400 m. However, range resolutions should be kept near 100 m and the lowest recorded height should be kept to a minimum (i.e., 150 m). Like that of sodar, many radar options include software subroutines that perform a variety of functions. It is important to purchase optional QA/QC software, if available, to provide an extra level of data validation.

The operating frequencies of all EM devices, including radars, are regulated by the Federal

Communication Commission (FCC). The allocated frequency for radar wind profilers for general use in the United States is 915 MHz, however, other permitted operating frequencies do exist. This frequency does provide the radar with good height range and minimum sample height, and should be adequate for most meteorological applications.

Like sodars, data recovery of radars is a function of atmospheric conditions and is highly variable. With radar, it is common to have several levels of invalid or missing data. This is typically due to a lack of humidity and insufficient levels in the refractive index in the atmosphere at those heights. Vertical range of radars is also variable and is a function of atmospheric conditions.

During precipitation events, radars measure the fall velocity of the precipitation instead of the air velocity. During these events, radars may appear to be generating reasonable wind estimates, however, it is more likely that the reported wind information is contaminated by the rainfall. During rain events, hail, or snow, the data should be flagged as suspect unless corrected in software. Assuming the vertical velocity averages to zero during the sampling interval, the vertical velocity measured during precipitation events represents the fall velocity of the precipitation. Knowing this, the horizontal winds can be corrected to an acceptable level, but the reported vertical velocity will be meaningless. During short duration precipitation events, the corrupted data may be pulled out of the data stream and an average produced using the remainder of the data set, thereby removing the problem. The radar user should be familiar with how the software handles precipitation events and should examine the data regularly to determine if the software handled the data processing correctly. Typical data capture efficiencies range from about 50% to near 90% and are variable from hour to hour.

4.8.2.3 RASS

RASS is an optional component of a radar system with the frequency of the acoustic source matched with the radar frequency to obtain a maximum reflective source. The power output of the acoustic source should be kept as high as possible to obtain the highest vertical level of virtual air temperature as possible. Data capture efficiencies are usually good, ranging from 70% to over 90%.

4.8.3 INSTALLATION

The following sections provide information on installation issues related to QA/QC concerns. General information concerning installation and siting of remote sensing devices may be found in the *On-Site Meteorological Program Guidance for Regulatory Modeling Applications* (U. S. EPA, 1987).

4.8.3.1 SODAR

Siting of sodars can best be accomplished by vendors or users who have experience with this type of remote sensing device. The complexities of sodars provide a challenge to the user who must optimize the conditions favorable for sodar technology while still making use of available sites in a given study area. It is suggested, until the time more data become available on proper installation procedures, that the vendor or an experienced sodar user be called upon to aid in the site selection and installation process.

A problem may exist at some potential monitoring sites due to the presence of acoustically reflective obstructions. The shapes of emitted acoustic pulses are not completely conical, but have side lobes that change shape and energy with frequency (see Figure 4.8.7). Reflective "fixed" echoes occur when acoustic (sound) waves emitted from sodars are reflected back to the receiver by fixed objects such as towers, buildings, trees, local terrain features, or other obstructions. These fixed echoes are often due to the energy contained in the side lobes of the emitted acoustic pulse. These fixed echoes have the effect of biasing the computed wind components u, v, and w.

It is extremely important to determine if the proposed sampling site has any potential for producing fixed echoes. Printing a facsimile chart sometimes reveals the presence of fixed echoes. This should be performed shortly after system setup, and repeated seasonally to aid in the determination if fixed echoes exists. Some fixed echoes may be avoided by constructing an acoustically absorbing shelter around the sodar antennas. These shelters are designed to absorb most of the energy released in the side lobes, providing a narrower beam, thus a cleaner acoustic signal. In general, it is recommended that the installer follow guidance provided in the *On-Site Meteorological Program Guidance for Regulatory Modeling Applications* (U. S. EPA, 1987). Section 3.0. Additional guidance includes the absence of obstructions in an 110° arc centered on the vertical axis or 40° centered on each beam (see Figure 4.8.8). In addition, if the system is to be installed near a building, the antennas should be oriented off the corners of the building. If the building does intercept the sound wave, the wave will be reflected away from the sodar due to the acute angles of the building's wall. Some manufacturers provide software routines which can detect fixed echoes and eliminate them from the consensus output.

All attempts should be made to avoid fixed echoes. However, if a limited number of sites are available and all have a possibility of producing fixed echoes, then the fixed echo detection software should be used to eliminate the problem. Special attention should be used during the acceptance test, described later, to determine if the fixed echo rejection routines are working properly.

The antenna does not necessarily have to point in one of the cardinal directions (i.e., north, south, east or west). System software allows the sodar to be setup in almost any direction, allowing the installer to point the beams away from obstacles that might interfere with the signal. For example, if the sodar is to be setup near a tower, the antenna should be oriented so the beams point away from the tower.

Another type of interference may occur from objects that emit noise such as local automobile traffic, nearby construction and overhead aircraft. Any acoustic source that emits its energy near the transmission frequency of a sodar has potential for interfering and degrading the quality of the sodar data. This type of interference is more difficult to detect because it tends to be seasonal, sporadic or random in nature. The potential for this problem may be reduced by installing acoustic absorbing shelters around the transceiver arrays. A simple test to determine if a problem exists at a given site is to set up the sodar and turn off the transmitter. Analysis of received energy will determine if the presence of interfering noise exists. If interference from remote sources is detected, it is recommended that the sodar be moved to an alternate site. The vendor or an experienced sodar operator should be consulted during the installation process to decrease the chance of contamination of these data.

4.8.3.2 RADAR

Siting a radar is somewhat more difficult than siting a sodar because of an increase in the potential for "ground clutter" to interfere with the return signal. Trees, power lines and even terrain features just a few meters above the radar can produce erroneous data due to reflected EM signals. Ground clutter often degrades the signal enough to render data useless, at least in the first few reported levels. Obstructions also produce false echoes similar to that of sodars. These false echoes also degrade the information in the first few reported levels.

Like sodar, radar beams have side lobes which emit energy to around 70° from vertical (Figure 4.8.9). These side lobes cause a higher degree of interference than sodars because radar return signals are typically very weak, so small amounts of energy reflected back to the receiver may cause large errors in the estimates of wind.

Therefore, radars should be setup away from tall buildings, power lines and other obstruction that may be a potential source of interference. The radar should also be situated on top of a small hill or building to decrease the potential for ground clutter contamination. The antenna does not necessarily have to point in one of the cardinal directions (i.e., north, south, east or west). System software should allow the radar to be setup in almost any direction, allowing the installer to point the beams away from obstacles that might interfere with the signal. For example, if the radar is to be setup near a tower, the antenna should be oriented so the beams point away from the tower.

The vendor or an experienced radar operator should be consulted during the installation process to decrease the chance of contamination of these data.

4.8.3.3 RASS

The user of a radar/RASS should follow the guidelines for installing a radar, as specified in Section 4.8.3.2. Contamination from external acoustic sources is only a minor problem but should also be avoided as outlined for sodars in Section 4.8.3.1. If a sodar/bistatic radar is being used to measure the virtual temperature then the installer should follow the guidelines for installing a sodar, with the addition of meeting the recommendations for installing a radar profiler.

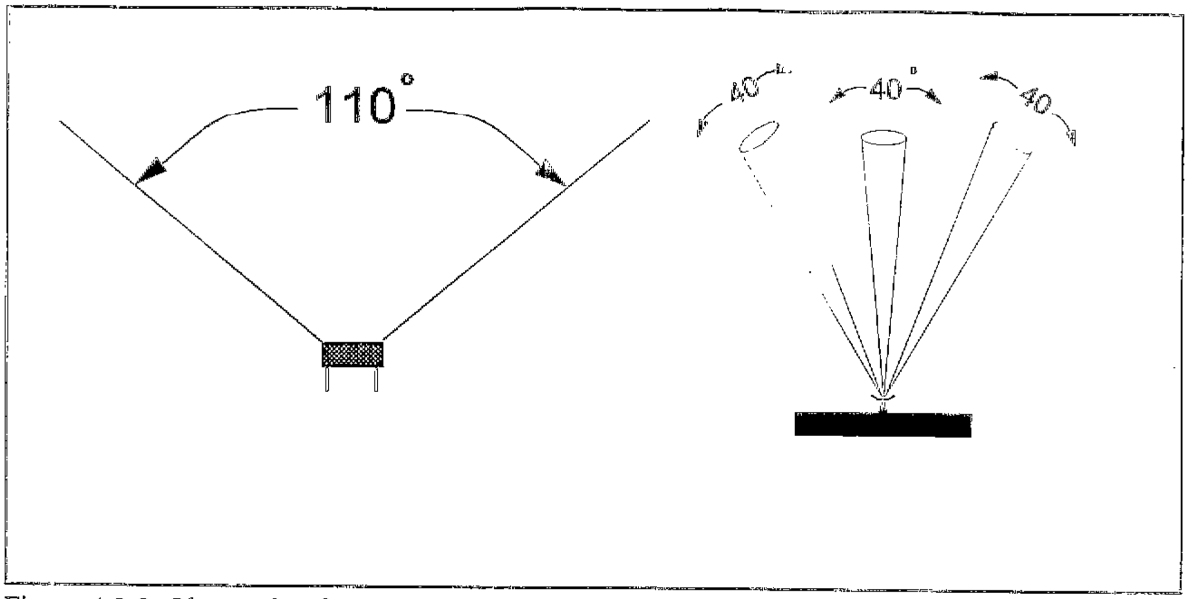

Figure 4.8.8 Obstruction free zone recommended for phased array and mono-static sodars.

4.8.4 ACCEPTANCE TESTING

Acceptance testing, as defined in Section 4.2.3, should be designed to determine if newly purchased or installed equipment is performing according to the manufacturer's specifications. The acceptance test is crucial for profilers since data produced by such instruments cannot be easily verified by simple tests. The following acceptance test is suitable for the sodar and may be easily modified for radar and RASS.

For meteorological remote sensors, an acceptance test should include comparison of data from the system to be tested with data from an acceptable in-situ sensor on a tower, tethersonde, a mini-sodar, kite, NWS rawinsonde, or similar systems. Although in-situ sensors do not qualify as transfer (or reference) standards, they do possess the required sensitivity to determine if the remote sensing device is operating normally (within some broad limits). The test should include the comparison of data at a minimum of three levels; all output generated by the remote sensing device (e.g., wind speed, wind direction, virtual air temperature), should be included in the comparison. One level should be the level of interest or application of the remote sensor data (i.e., effective stack height). Some manufacturers correct the horizontal wind components for vertical flow contamination. This correction is suitable in complex terrain where the average vertical wind velocity may be other than 0 m s^{-1}, indicating up-slope or down-slope flow. It is important to verify if this correction is being performed properly by the system. If the correction is being implemented, then it should be applied during the acceptance test if one is comparing the device with another remote sensor or anemometer that does not measure the vertical velocity. Figure 4.8.10 is a work sheet that may be used for performing an acceptance test on a sodar using a tethersonde as the gauge. The work sheet may be easily modified for use with other types of systems.

Determination of atmospheric stability, by an EPA approved method, should be the first step in an acceptance test of a profiling system. Atmospheric stability is important because it is an indication of the degree of turbulence present in the atmosphere. As discussed in Section 4.8.1, atmospheric turbulence provides the mechanism to reflect the transmitted signal back to the receiver. Pasquill-Gifford (P-G) stability categories of B or C (DOE, 1984) are probably the most desirable conditions for performing this test. These two stability classes typically provide a reasonable amount of turbulence to reflect sodar signals back to the receiver. In addition, the turbulence is such that it will not significantly "bounce" the tetherballoon, thereby avoiding unnecessary accelerations (which can introduce measurement errors) on the instrumentation attached to the tetherline. Ideally, surface wind speeds should be steady at 2 to 5 m s^{-1}. Wind speeds less than 2 m s^{-1} may be too variable for a reliable comparison, while wind speeds greater than 5 m s^{-1} will cause problems for the tethersonde as it is dragged out in more of a horizontal fashion rather than in a vertical profile.

The tetherballoon should be situated downwind and far enough away from the sodar so that it will not interfere (i.e., reflect) with the acoustic signal. It is suggested that a facsimile chart, or some indication of signal intensity, be printed during the test to determine if the tethersonde is interfering with the sodar. If a tower or other remote sensing device is being used then printing a facsimile chart is not required. If the tethersonde is interfering, it will show up on the facsimile chart as a solid line, (see Figure 4.8.11). The tetherballoon should be tethered at the first sampling height and data collected for at least 15 to 20 minutes. The time series information obtained from the tethersonde should match the time period for corresponding levels of the sodar sample. Average wind speeds and directions from both systems, along with their corresponding sample height, should then be entered into the work sheet. This procedure should be repeated to obtain similar information for at least two other heights.

The next step is to subtract the time averaged wind speed obtained from the tethersonde from that obtained from the sodar and record this information under the column titled "Wind Speed Discrepancy ." Repeat this procedure for the wind direction information. Determine the average discrepancy for each section. If the absolute value of the average discrepancy is less than the sum of the accuracies of the two instruments for wind speed and less than the sum of the accuracies of the two instruments for wind direction, then the profiler passes the acceptance test. If the test fails, it may be due to unsuitable atmospheric conditions at the measurement heights, the winds are not being corrected for contamination by the vertical velocity, or the average vertical wind velocity is other than 0 m s^{-1}. The test should then be repeated during conditions more favorable for sodar operation, mid-to-late morning, with clear skies and 10 m wind speeds between 2 and 5 m s^{-1}. If the sodar still fails the acceptance test, it may be informative to repeat the test using the u, v, and w components instead of the direction and speed information. This may reveal a mean vertical flow of something other than 0 m s^{-1}, an error in orientation, or some other problem.

The performance of meteorological remote sensors is dependant on meteorological conditions. Recognizing this, the meteorological conditions occurring during the test should be documented. This documentation should include the standard hourly observations including, current weather, ceiling, sky-cover, ambient temperature, wind speed and wind direction. An estimate of the

P-G class should also be included. If a tethersonde is used, it should be located so as not to interfere either with the tower sensors or the remote sensor.

It is very important to make sure the comparison data are processed in the same manner as the sodar or radar profiler being checked. The data from the tethersonde should be broken down into its u and v components. At the end of this sampling period, the components should be averaged and the resultant vector wind speed and wind direction calculated.

At some sites it may be possible to use National Weather Service rawinsonde data to perform the acceptance test. This test is somewhat more difficult to perform but will provide the data required to complete the test. The rawinsonde should be within 20 Km of the remote sensing site, in simple terrain, and in the same meteorological regime as that of the remote sensing instrument. The comparison should include a data time series long enough to have a large sample for every meteorological condition experienced at the site, and only data captured during similar meteorological regimes at both sites should be used in the comparison. Data at higher elevations should be used for the comparison since it is less likely that surface features will effect the data.

4.8.5 CALIBRATION AND PERFORMANCE AUDIT METHODS

Calibration of meteorological remote sensing devices is problematic since there is no correspondence with calibration of in situ instruments. Direct comparisons with rawinsondes, tetherballoons, or instrumented towers are not always adequate because of the difficulty in comparing point estimates with large volume estimates, as well as the problem of separation in time and space between the two platforms. Recent advances in QA/QC of sodars have led to the development of a transponder (responder) unit that simulates returned echoes to a sodar. This device allows the user to calibrate the instrument, much like using a constant speed motor to calibrate a cup anemometer. Due to costs required to build a similar system for EM systems, no similar device has been developed for radars.

Derivations of the first moments (i.e., wind speed in the direction of the energy pulse) are based on first principles. If the returned energy is strong enough, then reliable estimates of the radial wind speed may be obtained. From these derivations, an estimate of wind speed and direction are produced. If the remote sensing device has been calibrated, the meteorological conditions are favorable for the system, has no system problems and the signal-to-noise ratio is high, then the data produced may be considered of acceptable quality, assuming proper siting and calibration.

Second moments produced by remote sensing devices such as σ_w and σ_θ are typically based on statistics that are generated from wind speed and wind direction time series data. Statistically, these second moments are derived from spatially averaged time series with a data point being produced every 5 to 15 seconds. When wind speeds are low, errors in the estimate of wind direction increase. Some manufactures use more sophisticated techniques to estimate σ_w and σ_θ. These techniques are usually statistically based and provide a more refined estimate of these values, during certain atmospheric conditions. However, they still do not provide reliable estimates for all meteorological conditions. At this time σ_w and σ_θ from remote sensors are not recommended for use in regulatory dispersion modeling. Currently, there is an investigation underway to determine the usefulness of the reported σ_w and σ_θ values for use in regulatory modeling studies. If this investigation shows that these values are adequate for modeling, the next revision to this document will provide for their use in regulatory applications.

For these reasons, calibration and performance audit techniques for remote sensors should focus on the instrument electronics and other system components. If practical, the acceptance test should be repeated during the calibration process. This will ensure the highest quality data is being obtained. The following sections provide initial guidance on calibration and performance audit techniques for sodars, radars, and radars with RASS.

4.8.5.1 SODAR

To derive an estimate of the radial wind velocity, the sodar analyzes the frequency of the returned echo. The difference between the transmitted and returned frequency, the Doppler shift, is then used to derive the estimate of wind speed in the direction of the propagating acoustic wave. If atmospheric conditions are favorable and the signal-to-noise ratio is high, (i.e., a strong return signal is received) then an acceptable estimate of the wind speed within the sampling volume is produced.

Inherent to most sodars is a subsystem designed to identify malfunctions in the instrumentation. These subsystems differ with each manufacturer, but are of adequate sophistication to detect most instrument failures. These subsystems use both software and hardware to check system components such as signal amplifiers, analog-to-digital (A/D) converters, and voltage supplies. In multiple transducer units, the transducers can be checked by comparing their signal strength with their neighbor's signal strength. These tools should be used to determine system operation on a component basis. To determine overall system performance, a transponder (responder) should be used to induce signals into the system to determine if the instrument can correctly process the information. At a minimum level, the calibration should include feeding frequency shifted information into the transceiver array. If the information is analyzed correctly (within specified limits), then the calibration can be considered acceptable. If not, then the system should be serviced by the manufacturer. Manufacturer's instructions for performing these system tests should be followed until guidance is generated to standardize the procedures. In general, calibrations should be performed on a semi-annual basis, and whenever the system is moved or updated.

4.8.5.2 RADAR

Radar systems use software and hardware similar to that of a sodar to determine individual component operation. These checks are useful for determining if there are any component failures in the system and should be performed frequently enough to prevent long down times. In most situations, the software will provide the user with enough information to determine which component is malfunctioning. Due to the immense cost of building a transponder for radar systems, a series of component tests is used to monitor system performance. A series of test procedures defined to thoroughly test the functionality of the radar should be implemented to determine system performance. Key system components such as gain, power levels, and noise figures should be included in the test. Manufacturer's instructions for performing these systems tests should be followed until guidance is generated to standardize these tests. Calibrations should also be performed on radars on a semi-annual basis.

Tests are currently being conducted to determine a set of minimum requirements for calibrating sodars and radar. This section will be revised shortly to address any new requirements.

4.8.5.3 RASS

RASS systems use acoustic waves to provide the radar with a well defined refractive index structure for scattering the EM energy back to the receiver. The only real difference between a radar and a radar with RASS (except for some additional software) is the presence of acoustic sources. These acoustic sources typically consist of four transducers, one placed on each side of the radar antenna. Testing the radar component of the system should follow the guidelines discussed Section 4.8.5.2. This test should be performed on a semi-annual basis or when the system is moved or updated.

4.8.6 OPERATION, MAINTENANCE AND QC

Sodars, radars and RASS have automated operating systems and generally require minimal input from the user. Variables such as vertical range, range gates, averaging times, frequency, and power output may be adjusted if needed, but most of the system operations are automatic. The wind data should be stored in its u, v, w components, as this will insure minimal loss of information and more thorough data validation. This will also be useful in instances when the wind direction may be in question. Statistics such as number of valid return intensities and standard deviation of component values should also be stored as this information may be useful in detecting instrumentation problems. If a hard-disk drive is used for storing data, it should be checked as often as necessary to insure there is enough room to store data. This will avoid the potential for data loss due to insufficient disk space.

For the first few weeks after installation, the data should be checked on a daily basis to determine if the system is working properly. Time series plots of all variables should be produced and analyzed by a meteorologist or other qualified professional. This step is important for detecting any bias or anomalies in the data set. It is usually at this point that false echoes are detected. All inspections and maintenance activities should be documented in a site log book.

After a time when the site operator determines the system to be operating adequately, data should be plotted and checked on a weekly basis to determine system performance. This information is useful to aid in the evaluation of the system. For instance, data at certain heights are not recorded during particular meteorological conditions but are fine at other times. This information can also be used as an aid in determining system performance when the system appears to be malfunctioning.

Maintenance should include weekly checks of the antenna array, cables, and all connections. The antenna and antenna shelter should be checked and cleared of any debris. All cables should be systematically checked for any breaks due to weathering, animal bites or cuts due to human activities. If damage is detected, the cable should be immediately replaced. All other connections should be checked to insure proper operation. If manufacturer supplied hardware diagnostic routines are not automatically initiated, then they should be performed manually on a weekly basis.

Systematic routines used to inspect these data provide a level of quality control (QC). These QC checks should be performed by a meteorologist or other qualified professional who is familiar with the physical nature of profiler data sets. Such a person will more than likely spot and correct any problems. Without a qualified inspector, the potential exists for data to be corrupted and go unnoticed.

When a problem is found by the QC inspector, a discrepancy report should be issued which brings the users into the data QC loop. Their inspection and corrective action is reported back to the QC inspector closing the loop. With such a QC loop, the measurement system can be operated "in control" and valid data produced.

4.8.7 ESTIMATING ACCURACY AND PRECISION

At the present time, there are no accepted procedures for performing adequate calibrations to define system accuracy and precision of sodars, radars, or RASS. The difficulties were discussed in previous sections and will not be repeated here. New studies are necessary to provide valuable information on sodar and radar performance. These studies should enlighten our understanding of remote sensor performance and characteristics. At the completion of these studies, EPA will revise this Section to include any new information.

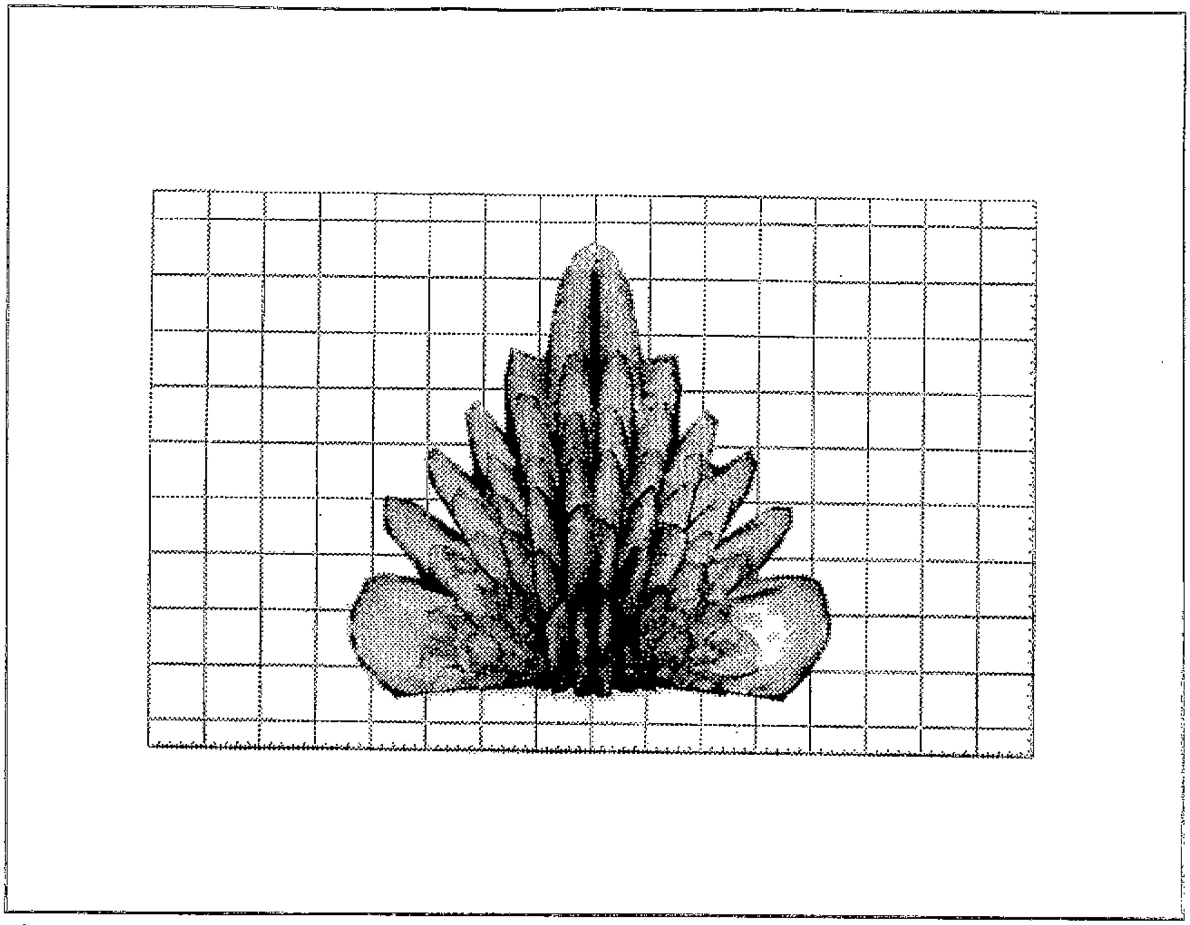

Figure 4.8.9 Radar beam pattern for 924 MHz vertical beam with no clutter fence.

Instrument Type____ Date:______________

Instrument Serial No.___________________________________ Time:______________

Acceptance Test Report by____

Specified Accuracy: Wind Speed ____________(m s^{-1})
Wind Direction____________(deg)

Tethersonde Serial No.______________________ Sonde Type____________________

Atmospheric Stability Surface Observations______________________________________

Number of Minutes in Average__________

Height (m)	Average Sodar Wind Speed (m s^{-1})		Average Tethersonde Wind Speed (m s^{-1})		Wind Speed Discrepancy (m s^{-1})
______	____________________	-	____________________	=	____________________
______	____________________	-	____________________	=	____________________
______	____________________	-	____________________	=	____________________
______	____________________	-	____________________	=	____________________

If absolute value of average discrepancy is ≤ 1.0 m s^{-1}, then system passes test (initial)__________

If absolute value of average discrepancy is > 1.0 m s^{-1}, then system fails test (initial)__________

Height (m)	Average Sodar Wind Direction (deg)		Average Tethersonde Wind Direction (deg)		Wind Direction Discrepancy (deg)
______	____________________	-	____________________	=	____________________
______	____________________	-	____________________	=	____________________
______	____________________	-	____________________	=	____________________
______	____________________	-	____________________	=	____________________

Figure 4.8.10 Worksheet for computing sodar discrepancy

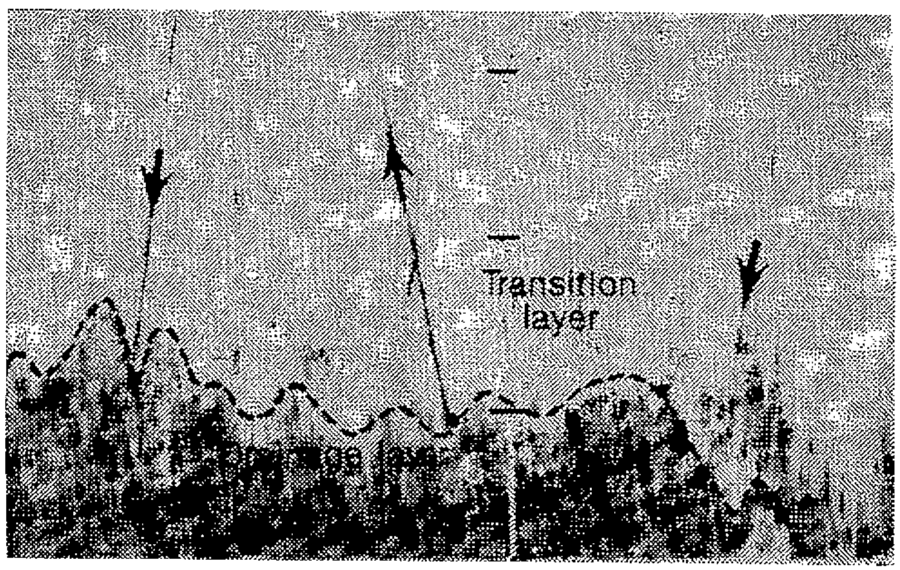

Figure 4.8.11 Sodar facsimile chart depicting tetherballoon interference (shown by arrows).

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PAMS METEOROLOGICAL MONITORING GUIDANCE

4.A.0 INTRODUCTION

The following section is an example of meteorological monitoring guidance tailored to a specific regulatory application. Most of the information given below is from the *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements* and other EPA documents.

4.A.1 OVERVIEW

Title 40 Part 58 of the Code of Federal Regulations (U. S. EPA, 1993) requires the States to establish a network of Photochemical Assessment Monitoring Stations (PAMS) in ozone nonattainment areas which are classified as serious, severe, or extreme. Each PAMS program must include provisions for enhanced monitoring of ozone and its precursors such as nitrogen oxides and volatile organic compounds. In addition, surface and upper-air meteorological monitoring is also required. The Environmental Protection Agency's (EPA) authority for enhanced monitoring is provided in Title I, Section 182 of the Clean Air Act Amendments of 1990.

The importance of high quality meteorological data for these nonattainment areas can not be overstated. Meteorology is a critical element in the formation, transport, and eventual destruction of ozone and its precursors. Consequently, meteorological data are essential to the development and evaluation of ozone control strategies (U. S. EPA, 1991). These evaluations include photochemical and receptor modeling, emissions tracking, and trend analysis. This section provides guidance for meteorological monitoring in support of PAMS. It is intended for use by Regional, State, and local EPA personnel involved in enhanced ozone monitoring activities. An overview of the PAMS meteorological monitoring requirements is presented in Table 4.A.1.

4.A.2 PAMS SITES

40 CFR Part 58 identifies up to four PAMS site types for a typical urban region. It is intended that meteorological monitoring activities will coincide with ozone and precursor sampling at each one of these sites. Site #1 is intended as the upwind/background characterization site and is located in the predominant morning upwind direction near the fringe of the urbanized area. Data collected at this site are needed to establish ozone and precursor concentrations which may be advected into the PAMS area from other regions. Site #2 is the maximum ozone precursor impact site and is typically located near the downwind boundary of the central business district where maximum precursor concentrations are expected. A second Site #2 may be required in larger urban areas. This additional site would be located near the edge of the central business district downwind of the second most predominant morning wind direction. Site #3 is the maximum ozone concentration site and is typically located 15 to 45 km downwind of the urban fringe area. Data collected at this site are needed to monitor maximum ozone concentrations occurring downwind of the area of maximum

precursor emissions. Site #4 is intended as the extreme downwind monitoring site and is located beyond Site #3. This site, which is downwind of the predominant afternoon wind direction, is needed to characterize the extreme downwind transport of ozone and precursor concentrations. Sites #1 and #2 are required for all PAMS networks whereas sites #3 and #4 are population dependent. Further details on PAMS site types may be found in the *Photochemical Assessment Monitoring Stations Implementation Manual* (U. S. EPA, 1994).

4.A.3 SURFACE METEOROLOGY

Guidance for surface meteorological measurements is provided in several documents They include the *On-Site Meteorological Instrumentation Requirements to Characterize Diffusion from Point Sources* (U. S. EPA, 1981); *Guide to Meteorological Instruments and Methods of Observation* (WMO, 1983); *Instructor's Handbook on Meteorological Instrumentation* (NCAR, 1985); *Ambient Monitoring Guidelines for Prevention of Significant Deterioration* (U. S. EPA, 1987a); *On-Site Meteorological Program Guidance for Regulatory Modeling Applications* (U. S. EPA, 1987b); and *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements* (U. S. EPA, 1989).

The surface meteorological variables to be measured at all PAMS sites include horizontal wind speed and wind direction, ambient air temperature, and relative humidity. Solar radiation, ultraviolet radiation, barometric pressure, and precipitation are to be measured at only one site (either Site #2 or #3). Application areas associated with these measurements are indicated in Table 4.A.2. A summary of instrument specifications for surface measurements are given in Table 4.A.3.

Meteorological instrumentation should not be mounted on or near solid structures such as buildings, stacks, water storage tanks, grain elevators, and cooling towers since they may create significant wind flow distortions. Instead, these instruments should be mounted on an open lattice 10 m tower since this structure creates the least amount of wind flow distortion. There are several types of open lattice towers: Fixed, tilt-over, and telescopic. A fixed tower is usually assembled as a one-piece structure from several smaller sections. This type of tower must be sturdy enough so that it can be climbed safely to install and service the instruments. Tilt-over towers are also one-piece structures, but are hinged at ground level. This type of tower has the advantage of allowing the instruments to be serviced at the ground. Telescopic 10 m towers are usually composed of three sections, each approximately 4 m in length. The top section is the smallest in diameter and fits inside the middle section which, in turn, fits inside the base section. The tower can be extended to a height of 10 m by use of a hand crank located at the lowest section. The top of the tower can be lowered to a height of about 4 m providing easy access to the wind sensors. Telescopic and tilt-over towers are not generally recommended for heights above 10 m. Regardless of which type of tower is used, the structure should be sufficiently rigid and properly guyed to ensure that the instruments maintain a fixed orientation at all times.

Table 4.A.1
Question/answer overview of PAMS meteorological monitoring requirements

Question	Answer
Where?	All serious, severe, and extreme ozone nonattainment areas.
When?	Routine continuous monitoring during the PAMS monitoring season (3 months per year minimum).
How Long?	Until area is redesignated as attainment for ozone.
How Many Sites?	2 to 5 surface sites per network plus one upper-air site.
What Interval?	Surface: Hourly. Upper-Air: 4 profiles per day (minimum).
What Variables?	Surface: Wind speed, wind direction, air temperature, and relative humidity at all sites. Solar radiation, ultraviolet radiation, barometric pressure, and precipitation at only one site. Upper-Air: Horizontal wind speed and direction required. Air temperature highly desired. Vertical wind speed, relative humidity, and barometric pressure optional.

Table 4.A.2
Applications for PAMS meteorological data.

Variable	Photochemical Modeling	Diagnostic Analysis	Receptor Modeling
Wind Speed	✓	✓	✓
Wind Direction	✓	✓	✓
Air Temperature	✓	✓	
Relative Humidity	✓	✓	
Solar Radiation	✓	✓	
Ultraviolet Radiation	✓	✓	
Barometric Pressure	✓	✓	
Precipitation		✓	✓

Table 4.A.3
Summary of sensor requirements for surface meteorological variables.

Variable	Height (m)	Range	Accuracy	Resolution	Time / Distance Constants
Wind Speed	10	0.5 to 50 m s^{-1}	±0.2 m s^{-1} + 5%	0.1 m s^{-1}	5 m (63% response)
Wind Direction	10	0 to 360°	±5°	1°	5 m (50% recovery)
Air Temperature	2	-20 to 40 °C	±0.5 °C	0.1 °C	60 s (63% response)
Relative Humidity	2	0 to 100 %RH	±3 %RH	0.5 %RH	60 s (63% response)
Solar Radiation	any	0 to 1200 W m^{-2}	±5%	1 W m^{-2}	60 s (99% response)
UV-A&B Radiation	any	0 to 12 W m^{-2}	±5%	0.01 W m^{-2}	60 s (99% response)
Barometric Pressure	2	800 to 1100 hPa	±1 hPa	0.1 hPa	60 s (63% response)
Precipitation	1	0 to 30 mm hr^{-1}	±10%	0.25 mm	60 s (63% response)

The objective of instrument siting (horizontal and vertical probe placement) and exposure (spacing from obstructions) is to place the sensor in a location where it can make measurements that are representative of the general state of the atmosphere in the region of interest. The choice of a site for a meteorological tower should be made with an understanding of the regional geography. Ideally, a meteorological tower should be located in an open level area away from the influence of obstructions such as buildings or trees. The area surrounding the site should have uniform surface characteristics. The specific site characteristics should be well documented. This is especially important where terrain with significant topographic features may introduce different meteorological regimes at the same time. Secondary considerations such as accessibility and security must be taken into account, but should not be allowed to compromise data quality.

Although it may be desirable to collocate the surface meteorological measurements with the ambient air quality measurements, this may not be possible at all PAMS sites without violating one or more of these criteria. Surface meteorological measurements in urban areas, where compliance with the above guidance may be precluded by the close proximity of buildings and other structures, present special difficulties. In such cases, the individual involved in the site selection needs to assess the likelihood that the data which will be collected at a given location will be valid for the intended application. In all cases, the specific site characteristics should be well documented. This is especially important in areas where surface characteristics and/or terrain are not uniform and whenever standard exposure and siting criteria can not be met.

The recommended sampling interval of the meteorological sensors by the data acquisition system is 10 seconds. Data for all variables should be processed to obtain one-hour averages. The observation time should correspond to the time at the end of the averaging period and should be recorded as local standard time. For example, a recorded time of 1500 (3 p.m.) corresponds to the sampling period from 1400 to 1500. The data acquisition system clock should have an accuracy of ±1 minute per week.

4.A.3.1 Wind Speed and Direction

Horizontal wind speed ($m\ s^{-1}$) and wind direction (degrees clockwise from geographical north) are essential to the evaluation of transport and dispersion processes. Measurements of wind speed and direction are also important in assessing atmospheric stability and turbulence. Wind speed is typically measured with a cup or propeller anemometer; wind direction is measured with a vane.

The standard height for surface layer wind measurements is 10 m above ground level (WMO, 1983). It is important that the tower be located in an area of level and open terrain. The wind sensor should be sited such that the horizontal distance to an obstruction is at least ten times the height of the obstruction. An obstruction may be man-made (e.g., building) or natural (e.g., trees).

The close proximity of tall buildings in downtown urban areas will often preclude strict compliance with the above exposure guidance. In such cases, the wind sensor should be sited such that measurements are reasonably unaffected by local obstructions and represent, as far as possible, what the wind at 10 m would be if there were no obstructions in the vicinity. Site characteristics should always be fully documented. This is especially important when standard exposure and siting criteria can not be obtained. Evans and Lee (1981) provide a discussion on the representativeness of 10 m wind data acquired in an urban setting where the average obstruction height is of the same order as the wind measurement height.

Turbulence in the immediate wake of the tower (even a lattice type) can be significant. Thus precautions must be taken to ensure that the wind measurements are not unduly influenced by the tower. The wind sensor should be mounted on a mast a distance of at least one tower width above the top of the tower, or if the tower is higher than 10 m, on a boom projecting horizontally from the tower. The sensor should be located at a horizontal distance of at least twice the diameter/diagonal of the tower 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 (i.e., into the prevailing wind).

A sensor with a high accuracy at low wind speeds and a low starting threshold is recommended for PAMS applications. Wind speed measurements should be accurate to $\pm 0.2\ m\ s^{-1}$ + 5% of observed speed from 0.5 to 50 $m\ s^{-1}$ with a resolution of 0.1 $m\ s^{-1}$. Light weight molded plastic or polystyrene foam should be employed for cups and propeller blades to achieve a starting threshold (lowest speed at which a rotating anemometer starts and continues to turn and produce a measurable signal when mounted in its normal position) of $\leq 0.5\ m\ s^{-1}$. Wind vanes or tail fins should also be composed of light weight molded plastic or polystyrene. The distance constant (the distance of air passage through the cup or propeller required for sensor to indicate a 1 - 1/e or 63.2% step change in the wind speed) should be ≤ 5 m at standard sea level density (1.2 $kg\ m^{-3}$). Wind direction measurement should be accurate to ±5° with a resolution of 1°. The starting threshold (lowest speed at which a vane will turn to within 5° of the true wind direction from an initial displacement of 10°)

should be ≤ 0.5 m s^{-1}. The delay distance (50% recovery from a 10° deflection) should be ≤ 5 m at standard sea level density. Overshoot must be ≤ 25% and the damping ratio should lie between 0.4 and 0.7.

4.A.3.2 Air Temperature

Air temperature (°C) is strongly correlated with extreme ozone concentrations. Consequently, it is an essential variable for PAMS applications. There are several types of temperature sensors; these include wire bobbins, thermocouples, and thermistors. Platinum resistance temperature detectors (RTD) provide accurate measurements with a stable calibration over a wide temperature range and are among the more popular sensors used in ambient monitoring.

The temperature sensor should be mounted on the tower 2 m above the ground and away from the tower a distance of at least one tower width from the closest point on the tower. This height is consistent with World Meteorological Organization (WMO, 1983) and EPA standard monitoring procedures. The measurement should be made over a plot of open, level ground at least 9 m in diameter. The ground surface should be covered with non-irrigated or unwatered short grass or, in areas which lack a vegetation cover, natural earth. Concrete, asphalt, and oil-soaked surfaces should be avoided. As such, the sensor should be at least 30 m away from any paved area. Other areas to avoid include large industrial heat sources, roof tops, steep slopes, hollows, high vegetation, swamps, snow drifts, standing water, and air exhausts (e.g., tunnels and subway entrances). The sensor should be located a distance from any obstruction of at least four times the obstruction height.

Temperature measurements should be accurate to ±0.5 °C over a range of -20 to +40 °C with a resolution of 0.1 °C. The time constant (63.2%) should be ≤ 60 seconds. Solar heating is usually the greatest source of error and consequently adequate shielding is needed to provide a representative ambient air temperature measurement. Ideally, the radiation shield should block the sensor from view of the sun, sky, ground, and surrounding objects. The shield should reflect all incident radiation and not reradiate any of that energy towards the sensor. The best type of shield is one which provides forced aspiration at a rate of at least 3 m s^{-1} over a radiation range of -100 to +1100 W m^{-2}. Errors in temperature should not exceed ±0.25 °C when a sensor is placed inside a forced aspiration radiation shield. The sensor must also be protected from precipitation and condensation, otherwise evaporative effects will lead to a depressed temperature measurement (i.e., wet bulb temperature).

4.A.3.3 Relative Humidity

Measurements of atmospheric humidity are essential to understanding chemical reactions which occur between ozone precursors and water vapor. The relative humidity (*RH*) is defined (List, 1951) as the ratio of the ambient mixing ratio (w) to the saturation mixing ratio (w_s) at a given air temperature and barometric pressure, i.e.,

$$RH \equiv 100 \frac{w}{w_s} \tag{1}$$

The ambient mixing ratio is defined as the ratio of the mass of water vapor to the mass of dry air.

The saturation mixing ratio is defined as the ratio of the mass of water vapor in a given volume of air saturated with respect to a plane surface of water to the mass of dry air. The mixing ratio can easily be determined if the relative humidity, air temperature, and barometric pressure are know by first computing the saturation vapor pressure (e_s) using the relation (Buck, 1981)

$$e_s = [1.0007 + (3.46x10^{-6}p)]6.1121\, e^{\frac{17.502T}{240.97+T}} \qquad (2)$$

where T is the ambient air temperature (°C) and p is the barometric pressure (hPa). The saturation mixing ratio is then computed using

$$w_s = \epsilon \left(\frac{e_s}{p - e_s} \right) \qquad (3)$$

where ϵ is 0.622. Substitution of RH and w_s into Equation yields the mixing ratio w.

Other measures of atmospheric humidity include vapor pressure (hPa), dew point temperature (°C), specific humidity (g kg^{-1}), and absolute humidity (g m^{-3}). All variables except for the relative humidity provide a complete specification of the amount of water vapor in the atmosphere. However, any of these variables can easily be derived from the relative humidity given the ambient air temperature and barometric pressure.

There are various techniques for measuring atmospheric humidity. However, the emergence of capacitive thin-film technology is now producing sensors which are reasonably accurate, reliable, compact, and inexpensive. Crescenti and Payne (1991) compared thin-film relative humidity sensors from two different manufacturers and found that they performed quite well. These sensors are becoming more common as they are easy to install and operate.

The relative humidity sensor should be installed using the same siting criteria as that for air temperature. The sensor should be housed in the same aspirated radiation shield as the temperature sensor at a height of 2 m above the ground. The accuracy should be ±3 %RH over a range of 10 to 95 %RH (±5 %RH from 0 to 10% RH and from 95 to 100 %RH) and -20 to +40 °C. Resolution should be 0.5 %RH with a time constant (63.2%) of ≤ 60 seconds.

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

4.A.3.4 Solar Radiation

Solar (sometimes called shortwave) radiation is a measure of the electromagnetic radiation of the sun and is represented as an energy flux (W m^{-2}). Solar radiation measurements are used in heat flux calculations, for estimating atmospheric stability, and in modeling photochemical reactions (i.e., ozone generation). The solar spectrum is comprised of ultraviolet radiation (0.10 to 0.40 μm), visible light (0.40 to 0.73 μm), and near-infrared (0.73 to 4.0 μm) radiation. About 97% of the solar radiation incident at the top of the earth's atmosphere lies between 0.29 and 3.0 μm (WMO, 1983). A portion of this energy penetrates through the atmosphere and is received at the earth's surface. The rest is scattered and/or absorbed by gas molecules, aerosols, various particulates, cloud droplets, and ice crystals.

A pyranometer is an instrument used for measuring energy fluxes in the solar spectrum. The sensor measures global solar (direct and diffuse) radiation when installed facing upwards in a horizontal plane tangent to the earth's surface. The sensing element of the pyranometer is usually a thermocouple which is protected by a clear glass dome to prevent entry of wavelengths outside the solar spectrum (i.e., long-wave radiation).

Solar radiation measurements should be taken in a location with an unrestricted view of the sky in all directions. In general, locations should be avoided where there are obstructions that could cast a shadow or reflect light on the sensor. In addition, the pyranometer should not be placed near light colored walls or artificial sources of radiation. In practice, the horizon should not exceed 5°, especially from the east-northeast through the south to the west-northwest (65° to 295° azimuth). A 5° horizon will obstruct only about 1% of the global radiation and thus can be considered negligible.

Pyranometers have no specific height requirement. Consequently, a roof top usually makes an ideal location for sensor placement. Lacking a suitable rooftop, an acceptable alternative would be a location directly south of the meteorological tower. Regardless of where the pyranometer is sited, it is important that the instrument be level to within 1° of horizontal. Any tilt from the horizontal will introduce significant errors (Katsaros and DeVault, 1986). To facilitate leveling, most pyranometers come with an attached circular spirit level.

Solar radiation measurements should have a total system accuracy of ±5% of the observed value with a resolution of 1 W m^{-2} over a range of 0 to 1200 W m^{-2}. The time constant (99%) should be ≤ 60 seconds. Manufacturer's specifications should match WMO (1983) requirements for either a secondary standard or first class pyranometer if reliable heat flux and stability parameters are to be calculated (Table 4.A.4). Photovoltaic pyranometers (which usually fall under second class pyranometers) should not be used for PAMS applications. While their cost is significantly less than that of thermocouple-type pyranometers, their spectral response is limited only to that of the visible spectrum. In essence, these sensors are nothing more than visible light indicators.

Table 4.A.4
WMO (1983) classification of pyranometers

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

4.A.3.5 Ultraviolet Radiation

Ultraviolet (UV) radiation may be divided into three sub-ranges (Table 4.A.5). Due to stratospheric absorption by ozone, UV radiation that reaches the surface is usually limited to wavelengths longer than 0.28 μm (UV-A and UV-B ranges). The most important photochemically active chemical species at these wavelengths are ozone, nitrogen dioxide, and formaldehyde. All three of these chemical species are important in the chemistry of ozone formation.

Table 4.A.5
Ultraviolet radiation classifications (WMO, 1983)

Type	Range
UV-A	0.315 to 0.400 μm
UV-B	0.280 to 0.315 μm
UV-C	0.100 to 0.280 μm

Ultraviolet pyranometers which have a spectral response spanning both the UV-A and UV-B (0.280 to 0.400 m) ranges are recommended for PAMS applications. The same siting criteria used for solar radiation measurements apply. The UV sensor should have an accuracy of ±5% over the range of 0 to 12 $W\ m^{-2}$, a resolution of 0.01 $W\ m^{-2}$, and a time constant (99%) of ≤ 60 seconds.

4.A.3.6 Barometric Pressure

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

There are numerous commercially available pressure transducers which range widely both in price and performance. Most of these sensors are capable of measuring barometric pressure with an overall accuracy of ±1.0 hPa over a range of 800 to 1100 hPa, a resolution of 0.1 hPa, and a time constant (63.2%) of ≤ 60 seconds.

The sensor can be place at the base of the tower or inside a shelter. Ideally, the sensor should be placed at 2 m above the ground. If needed, the pressure at 10 m (p_{10}) can be derived from the 2 m pressure (p_2) by using the hypsometric equation

$$p_{10} = p_2 e^{\frac{g(z_2 - z_{10})}{R_d T_v}} \tag{4}$$

where z_2 and z_{10} are 2 and 10 m, respectively, g is the acceleration due to gravity (9.81 m s^{-2}), R_d is the universal gas constant for dry air (287.05 J kg^{-1} K^{-1}), and T_v is the mean virtual air temperature (K) in the layer between z_2 and z_{10} which is computed by using

$$T_v = T(1 + 0.61\,w) \tag{5}$$

where T is the mean ambient air temperature (K) between z_2 and z_{10}, and w is the mixing ratio (g g^{-1}). The decrease in pressure between 2 and 10 m is 0.9 hPa for a typical ambient air temperature of 20 °C and a mixing ratio of 11 g kg^{-1} (75 %RH). Altitude of the station above mean sea level and the height of the pressure sensor above ground level should be carefully documented.

If the pressure sensor is placed indoors, accommodations should be made to vent the pressure port to the outside environment. One end of a tube should be attached to the sensor's pressure port and the other ended vented to the outside of the trailer or shelter so that pressurization due to the air conditioning or heating system is avoided. The wind can often cause dynamical changes of pressure in a room where a sensor is placed. These fluctuations may be on the order of 2 to 3 hPa when strong or gusty winds prevail.

4.A.3.7 Precipitation

The total amount of precipitation which reaches the ground is expressed as the depth to which it would cover a plane horizontal to the earth's surface in a given period of time. There are several rain gauge variations, including tipping-bucket, weighing-bucket, capacitive-siphon, and optical. The most common are the tipping and weighing-bucket which are cylindrical in shape with a 20 cm (8 inch) diameter collection orifice.

The rain gauge should be mounted on level ground so that its orifice is horizontal with the earth's surface. Obstructions (including the tower) should not be closer than two to four times their height from the instrument. The ground surface around the rain gauge should be natural vegetation. It should not be paved since this may cause splashing of rain into the gauge. The orifice of the gauge should be mounted 1 m above the ground.

Measurement accuracy for all types of rain gauges is influenced more by exposure than by variations in sensor design. High winds generally cause an underestimation of precipitation. Therefore, efforts should be taken to minimize the wind speed at the orifice, especially in open areas. This is best accomplished with the use of a wind shield. An example is the Alter type wind shield which consists of a ring with 32 free-swinging separate metal leaves approximately 1 to 2 cm above the collection orifice.

The rain gauge accuracy should be ±10% of the observed value with a resolution of 0.25 mm and a time constant (63.2%) of ≤ 60 seconds.

4.A.4 UPPER-AIR METEOROLOGY

40 CFR Part 58 requires at least one upper-air meteorological monitoring system for each PAMS affected area. Profiles of wind speed and wind direction are needed for use in transport and dispersion modeling. Profiles of air temperature are highly desired since this is a principle indicator of atmospheric stability. Other variables which can be measured, but not required, include vertical wind speed, relative humidity, and barometric pressure. EPA currently does not have any specific guidance on measurement levels and accuracies for any upper-air data. However, Tables 4.A.6 and 4.A.7 are WMO (1983) guidelines which can be used, but not required, as a model by those agencies responsible for implementing PAMS upper-air measurements.

Table 4.A.6
WMO (1983) observation levels for lower tropospheric soundings for operational and research purposes.

Variable	Interval (m)	Range (m)
Wind Speed and Wind Direction	50	0 to 300
	100	400 to 600
	200	800 to 1200
	300	1500 to 3000
Air Temperature and Relative Humidity	20	0 to 300
	50	350 to 1000
	100	1100 to 3000

Table 4.A.7
WMO (1983) observation accuracies for lower tropospheric soundings for operational and research purposes.

Variable	Accuracy	
Wind Speed	±0.5 m s^{-1} ±10%	WS ≤ 5 m s^{-1} WS > 5 m s^{-1}
Wind Direction	±10° ±5°	WS ≤ 5 m s^{-1} WS > 5 m s^{-1}
Air Temperature	±0.2 °C	
Relative Humidity	±5% ±1%	RH ≤ 95% RH > 95%

The upper-air measurements are intended for more macro-scale application than the surface meteorological measurements. Consequently, the location of the upper-air site does not necessarily need to be associated with any particular PAMS surface site. However, for convenience and logistics, the upper-air site can be collocated with a surface meteorology station. Depending on the meteorological conditions typically associated with high ozone concentrations in a given PAMS area, both upwind (Site #1) and/or downwind (Sites #3 and #4) sites may be appropriate locations for the upper-air monitoring. Factors that should be considered in selecting a site for the upper-air monitoring include whether the upper-air measurements for the proposed location are likely to provide the necessary data to describe the meteorological conditions associated with high ozone concentrations. Additional upper-air monitoring systems may be needed in areas where meteorological and photochemical processes are complex or where an internal thermal boundary layer has a significant role in ozone formation and transport.

A minimum of 4 profiles per day is required. These profiles should be acquired just prior to sunrise when the atmospheric boundary layer is usually the most stable; during mid-morning when the growth of the boundary layer is most rapid; during mid-afternoon when the surface air temperature is maximum; and during late-afternoon when the boundary layer depth is largest. The implementing agencies should make every attempt to acquire profiles in the first several hundred meters of the convective mixed layer. It is highly desired to obtain profiles of at least 1000 m or to the top of the convective mixed layer (which can easily exceed 2000 m on summer afternoons). However, not all measurement systems are capable of an extended height range. The implementing agencies are encouraged to acquire profiles with greater vertical range, higher resolution, and on a more frequent basis, if at all possible. Wind, temperature, and humidity profile data obtained by nearby National Weather Service (NWS) radiosondes may be used to partially fulfill and/or supplement the PAMS upper-air monitoring requirement.

In addition to the above variables, estimates are also required for the depth of the atmospheric boundary layer or mixed layer (i.e., mixing height). Reliable estimates of the mixing height are essential to dispersion modeling because this is the depth through which vertical mixing of pollutants normally occurs. The degree of dispersion within the mixed layer is primarily a function of atmospheric turbulence (i.e., wind flow, surface heating). The mixing height can be determined based on air temperature, turbulence, and/or aerosol concentration data.

The EPA recommended method for estimating mixing height requires measurement of the vertical temperature profile (Holzworth, 1964; 1972). In this method, the mixing height is calculated as the level above the ground in which the intersection of the dry adiabat (9.8 °C km^{-1}) from a mid-morning surface temperature and the sunrise temperature profile occurs. This concept of a mixing layer in which the lapse rate is roughly dry adiabatic is founded on thermodynamic principles and on operational use in regulatory dispersion modeling over the last two decades. Comparisons of mixing height estimates based on the Holzworth method with several other techniques indicate that all methods perform similarly in estimating the maximum afternoon mixing depth (Hanna, 1969; Irwin and Paumier, 1990). The Holzworth method is normally preferred because of its simplicity.

Another simple method for estimating the mixing height is by using an air temperature profile to derive a potential temperature profile. The potential temperature θ of an air parcel is defined as the temperature which the air parcel would have if it were expanded or compressed adiabatically from its existing pressure and temperature to a standard pressure p_o, which is generally taken as 1000 hPa (Wallace and Hobbs, 1977; Fleagle and Businger, 1980). An expression for the potential temperature can be derived by combining the First Law of Thermodynamics and the Ideal Gas Equation in terms of pressure p and air temperature T as

$$\theta = T\left(\frac{p_o}{p}\right)^{R_d/c_p} \qquad (6)$$

where R_d is the universal gas constant for dry air (287.05 J kg^{-1} K^{-1}), and c_p is the specific heat at constant pressure (1004 J kg^{-1} K^{-1}). Within a well mixed boundary layer, potential temperature is nearly a conserved property, i.e., it remains a constant value. The top of the mixed layer is typically marked by a rapid increase of potential temperature with height.

There are a variety of platforms for measuring upper-air meteorological data. These include aircraft, tall towers, balloon systems, and ground-based remote sensors. As with any measurement system, each has its advantages and disadvantages. The variables that can be measured with each upper-air system are summarized in Table 4.A.8. Note that with the exception of aircraft and tower, no one upper-air measurement system is capable of acquiring all of the variables listed in the table. Typical vertical ranges and resolutions for these systems are presented in Table 4.A.9. The choice of using any one or more upper-air measurement system is left to the discretion of the implementing agency. The information presented below provides some general background for each type of upper-air system.

Table 4.A.8

Meteorological variables that can be measured with various upper-air monitoring systems. Variables include horizontal wind speed and direction (WS/WD), vertical wind speed (W), air temperature (T), relative humidity (RH), and barometric pressure (BP).

System	WS/WD	W	T	RH	BP
Aircraft	✓	✓	✓	✓	✓
Tower	✓	✓	✓	✓	✓
Radiosonde	✓		✓	✓	✓
Tethersonde	✓		✓	✓	✓
Radar	✓	✓			
Sodar	✓	✓			
RASS			✓		

Table 4.A.9

Typical vertical ranges and resolutions for upper-air monitoring systems.

System	Range (m)	Resolution (m)
Aircraft	100 to 10,000	1
Tower	10 to 600	1
Radiosonde	10 to 10,000	5
Tethersonde	10 to 1,000	5
Radar	100 to 3,000	60 to 100
Sodar	50 to 1,000	25 to 50
RASS	100 to 1,500	60 to 100

4.A.4.1 Aircraft

Aircraft (both airplanes and helicopters) are the ultimate mobile observation station. They are capable of traversing large horizontal and vertical distances in a relatively short period of time. This platform can be equipped with meteorological instrumentation and an assortment of chemical sensors. Traditionally, aircraft are used for episodic field studies which often require extensive data sets for model evaluation. Lenschow (1986) provides an excellent overview of aircraft measurements in boundary layer applications. While an aircraft can provide detailed atmospheric observations over large areas, the total sampling time per flight (typically 6 to 8 hours) is relatively short because of fuel considerations. Aircraft may also be subject to Federal Aviation Administration (FAA) restrictions on flight paths over urban areas. In addition, the operating cost for this type of platform is extremely expensive.

4.A.4.2 Tall Towers

In some instances it may be possible to use existing towers which may be located in PAMS areas to acquire vertical profiles of atmospheric boundary layer data. Radio and television transmission towers, which may be as tall as 600 m, can be equipped with in-situ meteorological sensors at many levels. An advantage to using a tower is the ability to run an unattended data acquisition system. Also, data can be collected under all weather conditions. However, the main disadvantage of using a tower is the inability to determine the mixed layer height during most of the day. When moderate to strong convective conditions exist, the mixed layer height easily exceeds that of the tallest towers. Another disadvantage is the potentially high cost of maintenance, especially during instances when the instrumentation needs to be accessed for adjustments or repairs.

4.A.4.3 Balloon Systems

Balloon-based systems offer a relatively inexpensive means for upper-air meteorology measurements. There are two types of balloon systems: Radiosonde (sometimes called rawinsonde) and tethersonde.

The radiosonde is reliable, robust, light weight, and relatively small. The radiosonde is expendable, and can be mass produced at low cost. The radiosonde is comprised of sensors, a tracking device, and a radio transmitter. This sensor package is suspended from a hydrogen or helium filled balloon and is released at the surface. Air temperature is measured with a bimetallic strip, ceramic semi-conductor, or a wire resistor. The relative humidity is measured with a carbon hygristor or a thin-film capacitive chip. The barometric pressure is obtained with the an aneroid capsule. Ground-based radar is used to determine horizontal wind speed and direction. The radiosonde is capable of easily traversing the depth of the troposphere and reaching well into the stratosphere.

A tethersonde system is comprised of a tethered balloon with several sonde packages attached to the line. Variables measured include horizontal wind speed and direction, air temperature, relative humidity, and barometric pressure. These data are telemetered to the ground by radio or by conductors incorporated within the tethering cable. The tethersonde is capable of reaching altitudes up to 1000 m. However, this system can only operate in light to moderate wind conditions (5 m s^{-1} at the surface, 15 m s^{-1} aloft). A tethered balloon may also pose as an aviation hazard and is subject to FAA regulations. A permit must be obtained for permission to operate such a system.

Low cost is the main advantage for these systems, as well as ease of transport and relatively low maintenance. The main disadvantage for balloon systems is that they can be very labor intensive, especially if data are needed on an frequent basis. In addition, vertical wind speed can not measured by either balloon system.

4.A.4.4 Ground-Based Remote Sensors

Ground-based remote sensors have become effective tools for acquiring upper-air information and have played an increasingly important role in atmospheric boundary layer studies. However, there is a distinct void in available guidance needed to help potential users in the regulatory community. Because of their unique nature and constant evolution, EPA guidance for remote sensors is more generic than that which already exists for many of the well established in-situ meteorological sensors. Efforts are underway to provide more clearly defined guidance and standard operating procedures which will appear in the next edition of the *Quality Assurance Handbook for Air Pollution Measurement Systems, Volume IV: Meteorological Measurements* (EPA, 1989).

There are two basic types of remote sensing systems used to acquire three-component wind velocity profiles: Radar (radio detection and ranging) and sodar (sound detection and ranging). Radars (also called wind profilers) transmit an electromagnetic signal (~ 915 MHz) into the atmosphere in a predetermined beam width which is controlled by the configuration of the transmitting antenna. Sodars (also called acoustic sounders) transmit an acoustic signal (~ 2 to 5 KHz) into the atmosphere in a predetermined beam width which is also controlled by the transmitting antenna. The radar has a range of approximately 100 to 3000 m with a resolution of 60 to 100 m. The sodar has a range of about 50 to 1000 m with a resolution of about 25 to 50 m.

Both systems transmit their respective signals in pulses. Each pulse is both reflected and absorbed by the atmosphere as it propagates upwards. The vertical range of each pulse is determined by how high it can go before the signal becomes so weak that the energy reflected back to the antenna can no longer be detected. That is, as long as the reflected pulses can be discerned from background noise, meaningful wind velocities can be obtained by comparing the Doppler shift of the output signal to that of the return signal. A positive or negative Doppler shift indicates whether the radial wind velocity is moving towards or away from the transmitting antenna. The attenuation of a transmitted pulse is a function of signal type, signal power, signal frequency, and atmospheric conditions. Radar signal reflection depends primarily on the presence of an index of refraction gradient in the atmosphere which varies with temperature and humidity. Sodar signal reflection depends primarily on the presence of small scale atmospheric turbulence. The reflected signals received by either a radar or sodar are processed in a computer by signal conditioning algorithms.

In order to obtain a profile of the three-component wind velocity (U, V, W), one vertical beam and two tilted beams are needed. The two tilted beams are usually between 15° and 30° from the vertical. These two beams are also at right angles to each other in azimuth. Each antenna transmits a pulse and then listens for the reflected signal in succession. After all three antenna perform this function, enough information is available to convert the radial velocities into horizontal and vertical wind velocities by using simple trigonometric relationships.

There are two types of antenna configurations for radars and sodars: Monostatic and phased array. Monostatic systems consist of three individual transmit/receive antennas. Phased array consist of a single antenna array which can electronically steer the beam in the required directions. Vertical panels (also known as clutter fences) are usually placed around the antennas. This effectively acts to block out any stray side-lobe echoes from contaminating the return signal of a radar. For sodars, these panels cut down on the side-lobe noise which may be a nuisance to nearby residents and also prevents any background noise which may contaminate the return signal.

A radio acoustic sounding system (RASS) utilizes a combination of electromagnetic and acoustic pulses to derive a virtual air temperature profile. A RASS usually consists of several acoustic antennas placed around a radar system. The antennas transmit a sweep of acoustic frequencies vertically into the atmosphere. As the sound pulses rise, the speed of the acoustic wave varies according to the virtual air temperature. Concurrently, a radar beam is emitted vertically into the atmosphere. The radar beam will most strongly reflect off the sound wave fronts created by the acoustic pulses. The virtual air temperature is computed from the speed of sound which is measured by the reflected radar energy. The typical range of a RASS is approximately 100 to 1500 m with a resolution of 60 to 100 m.

Unlike in-situ sensors which measure by direct contact, remote sensors do not disturb the atmosphere. Another fundamental difference is that remote sensors measure a volume of air rather than a fixed point in space. The thickness of the volume is a function of the pulse length and frequency used. The width of the volume is a function of beam spread and altitude.

Siting of these profilers is sometimes a difficult task. Artificial and natural objects located near the sensors can potentially interfere with the transmission and return signals, thereby contaminating the wind velocity data.

Since sodars utilize sound transmission and reception to determine the overlying wind field, a clear return signal with a sharply defined atmospheric peak frequency is required. Thus, consideration of background noise may put limitations on where a sodar can be located. External noise sources can be classified as active or passive, and as broad-band (random frequency) or narrow-band (fixed frequency). General background noise is considered active and is broad-band. If loud enough, it can cause the sodar software to reject data because it can not find a peak or because the signal-to-noise ratio is too low. The net effect is to lower the effective sampling rate due to the loss of many transmission pulses. A qualitative survey should be conducted to identify any potential noise sources. A quantitative noise survey may be necessary to determine if noise levels are within the instrument's minimum requirements.

Examples of active, broad-band noise sources include highways, industrial facilities, power plants, and heavy machinery. Some of these noise sources have a pronounced diurnal, weekly, or even seasonal pattern. A noise survey should at least cover diurnal and weekly patterns. Examination of land-use patterns and other sources of information may be necessary to determine if any seasonal activities may present problems.

Examples of active, fixed-frequency noise sources include rotating fans, a back-up beeper on a piece of heavy equipment, birds, and insects. If these noise sources have a frequency component in the sodar operating range, they may be misinterpreted as good data by the sodar. Some of these sources can be identified during the site selection process. One approach to reducing the problem of fixed frequency noise sources is to use a coded pulse, i.e., the transmit pulse has more than one peak frequency. A return pulse would not be identified as data unless peak frequencies were found in the return signal the same distance apart as the transmit frequencies.

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

The radar, sodar, and RASS antennas should be aligned and tilted carefully as small errors in orientation or tilt angle can produce unwanted biases in the data. True North should also be established for antenna alignment. Installation of the antennas should not be permanent since problems are very likely to arise in siting the profilers in relation to the tower and other objects that may be in the area. One final consideration is the effect of the instrument on its surroundings. The sound pulse from a sodar and RASS is quite audible and could become a nuisance to residents who might happen to live near the installation site.

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