METEOROLOGICAL MEASUREMENT SYSTEMS

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Preface

This material has been used in connection with courses in the School of Meteorology at the University of Oklahoma. The first course in instrumentation is a junior level course with prerequisites of mathematics through calculus and ordinary differential equations and one year of calculus-based physics. The second course is first-year graduate level.

The objective of the courses is to examine the physical principles of meteorological sensors, to develop static and dynamic performance concepts, and to explore the concepts of meteorological measurement systems.

SI units are used throughout this text along with commonly accepted units such as °C for temperature and mb for pressure.

The first twelve chapters are presented in the order that F.V.B. has found useful in presenting lecture material. After discussing barometry (chap. 2), it is somewhat easier to present the material on static characteristics (chap. 3) as the students have the pressure sensor examples to consider. Dynamic performance characteristics are presented as needed. Chapter 8, Dynamic Performance Characteristics, Part 2, may be skipped in an undergraduate course. Chapter 13, Sampling and Analog-to-Digital Conversion, may be inserted almost anywhere in the course.

Some fundamental concepts, such as static and dynamic performance, are presented after discussion of sensors, so that students will be able to immediately apply these concepts to sensors they have discussed and extend their knowledge of these sensors.

Throughout, in situ or immersion sensors are discussed with only a few exceptions. There is a brief mention of radar in connection with rain gauges because radar–rain gauge comparisons are done so often. It is useful to include some treatment of radar so the student can see what the problem is. Visibility and cloud height sensors are included because they are part of some surface observing systems.

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METEOROLOGICAL MEASUREMENT SYSTEMS

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Overview

Measurements are required to obtain quantitative information about the atmosphere. Elements of a good measurement system, one that produces high-quality information, are briefly described in the following sections. All of these items are, or should be, of concern to everyone who uses data. None may be safely delegated, in their entirety, to those who have little or no interest in the ultimate use of the data.

1.1 Instrument Design and Selection

An instrument is a device containing at least a sensor, a signal conditioning device, and a data display. In addition, the instrument may contain an analog-to-digital converter, data transmission and data storage devices, a microprocessor, and a data display. The sensor is one of the essential elements because it interacts with the variable to be measured (the measurand), and generates an output signal proportional to that variable. At the other end of this chain, a data display is also essential, for the instrument must deliver data to the user.

To understand a sensor, one must explore the physics of the sensor and of sensor interaction with the measurand. There is a wide variety of sensors available for measuring pressure, temperature, humidity, and so on, and this text discusses each individually. Therefore, each chapter must deal with many different physical principles.

1.1.1 Performance Characteristics

Sensor performance can be described by reference to a standardized set of performance definitions. These characteristics are used by manufacturers to describe instruments and as purchase specifications by buyers.

1.1.1.1 Static

Static characteristics (chap. 3) are those obtained when the sensor input and output are static (i.e., not changing in time). Static sensitivity is an example of a static characteristic and is particularly useful in sensor analysis. When raw sensor output is plotted as a function of the input, the slope of this curve is called the static sensitivity. Relating static sensitivity to fundamental physical parameters is a systematic way of revealing sensor physics and leads to an understanding of the sensor and of how to improve the design.

1.1.1.2 Dynamic

Dynamic characteristics are a way of defining a sensor response to a changing input. The most widely known dynamic performance parameter is the time constant, discussed in chap. 6. This parameter is appropriate to systems whose dynamic performance can be modeled with a simple first-order, ordinary differential equation. More complex dynamical systems are described in chap. 8. Again, the goal is to relate these dynamic characteristics to physical parameters.

1.1.2 Functional Model

A measurement system interacts with the atmosphere and delivers data (information about the desired atmospheric variables) to the users. Common features of a measurement system are shown in fig. 1-1 in functional form. A measurement system may comprise some or all of these blocks, plus many more in a complex system. The blocks essential to any measurement system are 1, the sensor, 2, analog signal conditioning (ASC), and 7, the display. ADC is analog-to-digital converter, and DSC is digital signal conditioning. Raw input is X_i, the measurand (for example, air temperature), and final output is Y_7 (for example, temperature in degrees Celsius).

Block 1 is the sensor with input X_i, called the measurand, and raw output Y_1. A sensor is a transducer, i.e., a device that converts energy from one form to another. An instrument may contain several transducers to convert the energy from the measurand through several steps to a useful form such as electrical voltage. Here the sensor is the primary transducer, the one that interacts with the atmosphere, and block 1 contains only this sensor. Another transducer, if used, will be modeled in the next block. The output of block 1 is the primary transducer raw output in units appropriate to that device.

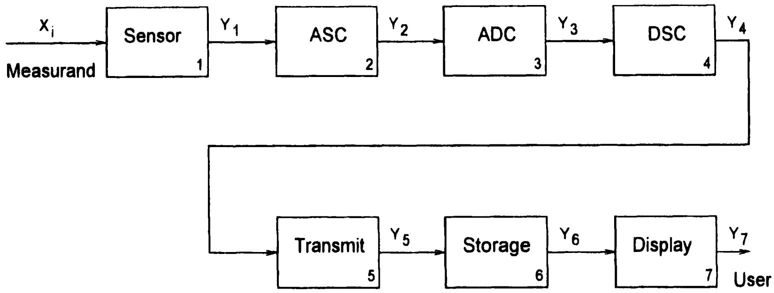

Fig. 1-1 Functional model of a simple measurement system.

EXAMPLE

A mercury-in-glass thermometer may be modeled with blocks 1, 2, and 7. In the sensor, block 1, heat energy is converted into a change in volume of the mercury in the bulb and thus into the height of the mercury column relative to some arbitrary index. The diameter of the column relative to the volume of the bulb is a form of signal conditioning, block 2, which sets the amplification of the thermometer. A smaller column diameter forces the mercury to rise further for a given temperature increase. The input into block 1 (X_i) is air temperature in Kelvin or degrees Celsius while the raw output, Y_1, is the volume of the mercury. After amplification in block 2, the raw output becomes Y_2, the height of the mercury column. The scale etched into the glass, the display (block 7), provides the calibration information that allows the user to translate the raw height, Y_2, into temperature, Y_7.

We may deduce, through calibration, a polynomial to relate the raw sensor output, Y_1, to an estimate of the measurand; thus $X_1 = c_0 + c_1 Y_1$ (a first-order polynomial is used in this example but any order polynomial can be used). The quantity X_1 is an estimate of X_i, based on knowledge of the signal Y_1. If an instrument has seven functional blocks, as in fig. 1-1, we must have a calibration for each block in order to estimate X_7 from Y_7 or, alternatively, we could have obtained the calibration for the complete system in one step using $X_7 = c_0 + c_1 Y_7$. The measurand is truly unknowable because all instruments extract some energy from the measurand and add some noise to the output signal. Therefore, X_i can only be estimated and never known exactly.

X_i and Y_n are signals, that is, information-bearing quantities such as temperature, wind speed, shaft rotation rate, voltage, current, resistance, frequency, and so on, X_i, Y_1, and Y_2 are always analog signals, that is, signals whose information content is continuously proportional to the measurand. Block 2 contains analog signal conditioning (ASC) which may include secondary transducers, an amplifier to provide gain and offset, and filters to reduce high-frequency noise.

EXAMPLE

A cup anemometer is a sensor that converts horizontal wind speed to angular rotation rate of a shaft that is connected to the cup wheel. The sensor input is wind speed in m s-1 and the output is shaft rotation rate in radians s^{-1}. There is usually a secondary transducer, such as a dc generator, connected to the shaft to convert rotation rate to a voltage. This voltage is continuously proportional to the shaft rotation rate which in turn is proportional to the wind speed. Instead of a dc generator, magnets can be used to produce an ac pulse each time the shaft rotates (several pulses can be generated for each shaft rotation, using multiple magnets). In this case, the raw sensor output is shaft rotation rate in Hz.

Block 3 is an analog-to-digital converter (ADC) and is present in most modern measurement systems to convert analog signals to discrete values, i.e., digital. The output signal of an ADC is a stream of numbers representing the value of the input signal. Conversions are usually done at discrete time intervals; thus the output stream is discrete in both value and time.

EXAMPLE

A voltage proportional to wind speed is the input to an ADC. It is set to sample this voltage at 3-second intervals and convert the voltage value of each sample to a binary number that can be read by a microprocessor. These binary numbers can be thought of as integers (as in the programming languages Basic, FORTRAN, or C). Then the ADC output stream is an integer every 3 seconds. There is some scaling applied, so that an integer value of 0 might represent 0 m s^{-1} whereas 500 stands for 25 m s^{-1} and 1000 stands for 50 m s^{-1}.

After the signal is in digital form, it may be manipulated by digital processing elements (DSC = digital signal conditioning), most commonly a microprocessor, represented in block 4. It is convenient to apply the calibration equation here, to correct for nonlinearities, compensate for secondary inputs, format the output, and, in some cases, to drive the output display.

Blocks 5 and 6 represent the operations of data transmission and storage that may not be present in simpler systems but are common in larger measurement systems. Data may be transmitted via a hard-wired connection, telephone lines, a direct radio link, or satellite relay. Data storage could involve anything from holding temporary data to final archiving.

The data display, block 7, is required in even the simplest system as it is the mechanism for user access to the data. It may be a simple analog meter indicator (temperature scale on a mercury-in-glass thermometer) or a complex CRT graphical presentation.

In fig. 1-1, the system input is shown as only a single input, the measurand. In reality, most sensors have some sensitivity to other, unwanted, signals referred to as secondary inputs. In a well-designed instrument, secondary inputs are minimized or controlled but they can seldom be removed completely or ignored. As discussed below, secondary inputs are sources of error in a measurement system.

1.1.3 Sources of Error

There are four basic categories of errors (observed minus actual) in a meteorological measurement system: static, dynamic, drift, and exposure.

1.1.3.1 Static

Static errors are measured when the input is held steady and the output becomes essentially constant. These are the errors remaining after applying a calibration equation. They may be deterministic (e.g., hysteresis, residual nonlinearities, and sensitivity to unwanted inputs such as temperature) or random (noise). See chap. 3 for additional information on static performance characteristics and static errors.

1.1.3.2 Dynamic

Dynamic errors, defined in chaps. 6 and 8, are those due to changing inputs. By definition, dynamic errors disappear when the input is held constant long enough for the output to become constant. Thus dynamic effects are not present during static testing. Every sensor exhibits some time lag and may also produce more complex error modes. See chaps. 6 and 8 for a complete treatment of dynamic errors.

1.1.3.3 Drift

Drift is due to physical changes that occur in a sensor over time. This is a special category of error because these errors are not truly static, nor are they considered to be dynamic, because they are independent of the rate of change of the input. Drift errors are difficult to account for in most measurement systems; the most direct way to compensate for them is frequent calibration. Sensors that drift linearly with time can in principle be corrected, but this can lead to additional uncertainty in the final measurement. And there are many cases where drift does not change linearly with time; sometimes it changes abruptly.

1.1.3.4 Exposure

This is a very special category of errors. They are due to imperfect coupling between the sensor and the measurand. For example, consider the case of using a thermometer to measure air temperature. The sensor will never be at exactly the same temperature as the air because of dynamic errors. Steps can be taken to minimize the differences between the air temperature and the temperature of the sensor, for example, by blowing air on the sensor and shielding it from radiation and conduction sources. However, a temperature sensor will respond to radiative energy exchanges with the sun or other objects and to conductive heat transfer through mechanical supports as well as to the desired convective heat transfer to or from air moving over the sensor. The magnitude of these errors will be a function of global solar radiation, shielding, and the efficiency of convective heat transfer with the air that is strongly dependent upon the rate of air flow over the sensor. These sources of error are not present in the calibration laboratory and are not included in sensor specifications. Therefore, statements about instrument errors assume no exposure error. In a well designed, properly calibrated, and properly maintained measurement system, exposure error can easily exceed all other error sources.

In general, instruments report their own state, which is not necessarily the state of the atmosphere unless great care is taken to provide good exposure. A cup anemometer actually reports the rotation rate of its cup wheel, not the wind speed. If the cup wheel bearings are in good condition and the wind speed is steady, then there is a known relationship between the rate of rotation and the wind speed, determined by the calibration.

Static and dynamic errors are measured during laboratory testing and can be well documented, certainly better than drift or exposure error.

1.2 Standards

There are several kinds of standards that are relevant to meteorological measurement systems: calibration, performance specification, exposure, and procedural. All must be considered in system design and evaluation.

1.2.1 Calibration

Calibration standards are maintained by standards laboratories in each country, such as by the National Institute of Standards and Technology (NIST) in the United States. Standards for temperature, humidity, pressure, wind speed, and for many other variables are maintained. The accuracy of these standards is more than sufficient for meteorological purposes. Every organization attempting to maintain one or more measurement stations must have some facilities for laboratory calibration, including transfer standards. These are standards used for local calibrations that can be sent to a standards laboratory for comparison with the primary standards. This is what is meant by traceability of sensor calibration to NIST standards. Ideally, the calibration of all sensors can be traced back to such a standards laboratory.

1.2.2 Performance

Performance specification standards refer to the terminology, definitions of terms, and the method of testing static and dynamic sensor performance. The American Society of Testing and Materials (ASTM) has been active in establishing these standards. We must agree on use of terms such as time constant, response time, sensor lag, and so on, and the definition of the chosen terms. It is essential that there be a standard method of testing sensors to determine their performance characteristics. Without these standards, vendor performance specifications would be difficult to interpret.

1.2.3 Exposure

Exposure standards are necessary to define what is meant by adequate exposure for certain classes of applications. For example, what is meant by surface wind speed and direction on the synoptic scale? Is it acceptable to mount the anemometer beside a building? How about on the roof of a building? For synoptic observations, we want the measurement to be representative of a large area. An anemometer mounted beside a building or on its roof provides measurements strongly influenced by the building and therefore are not representative of a large area. At what height above ground should measurements be made? The mean wind speed approaches zero near the ground, so an anemometer should be mounted at a standard height above ground. Norment (1992) and Oost (1991) have shown that the shape of the sensor itself, and that of the supporting structure, can also perturb wind flow. To make measurements comparable, there should be, at least, a standard mounting height and some standards about the proximity of obstructions.

The WMO (World Meteorological Organization) specifies a standard mounting height for wind instruments of 10 m above level, open terrain. The distance between the anemometer and an obstruction (buildings, trees, etc.) must be at least ten times the height of the obstruction. This precludes mounting an anemometer on the roof of a building.

Temperature sensors, according to WMO recommended practice, should be exposed in a radiation screen, with or without forced ventilation, at a height of 1.25 m to 2.00 m above a level ground surface. The screen must not be shielded by or close to trees, buildings or other obstructions. A measurement site must not be on a steep slope or in a depression where thermal conditions might not be representative of the larger scale. Exposure on top of buildings is not recommended because of the vertical temperature structure in the atmosphere and the perturbation caused by buildings. Where snow is persistent, it is acceptable to maintain the sensor at a constant height above the snow surface.

Precipitation measurements are best made in clearings surrounded by brush and trees to reduce the wind effect. There is frequently a requirement to locate the rain gauge, with other sensors, close to the data logger. One way to resolve this conflict is to equip each rain gauge with a wind screen. This is a screen designed to minimize the effect of wind on the gauge catch. See chap. 9 for additional details.

In the real world, some of these requirements are mutually exclusive and so many sites fail to meet all of the exposure specifications. Therefore, it is necessary to document carefully and completely sites with photographs to show the terrain, especially the wind fetch.

1.2.4 Procedural

Procedural standards refer to selection of data sampling and averaging periods and to simple algorithms for commonly computed quantities. These standards have been evolving slowly without much compliance so far. When data are used only within one network and for narrowly defined goals, these standards are not so important. However, when data from several networks are combined or data are used in more diverse applications, adherence to procedural standards becomes significant. Implementation of these standards requires local processing capability, usually found in the data logger, the data collection platform, or in another local system element.

1.3 System Integration

Design of a measurement system is powerfully affected by considerations other than the choice of sensor and data logger. Selection of the measurement platform, data communication system, and type of power have a profound effect on overall system design. Communication system limitations may dictate the location of remote sites, forcing compromises in site location. Power limitations may prohibit the use of certain types of sensors.

Sensors are typically mounted on a stationary platform (a simple mast or tall tower) or on a moving platform (balloons, planes, ships, etc.). Ideally, data are communicated in real time from the measurement site or platform to a central archiving facility. In some cases, real-time communication is not possible but, instead, data are manually collected at periodic intervals, usually in some electronic form. Availability of electrical power, or the lack of it, may seriously affect the system design.

1.3.1 Instrument Platforms

It is not surprising that virtually every type of instrument platform is used in meteorology because the atmosphere is so extensive and because most of it is quite inaccessible. These platforms include masts, instrument shelters, tall towers, balloons, kites, cars, ships, buoys, airplanes, rockets, and satellites. Synoptic data platforms include balloons and satellites supplemented by buoys and ships over the ocean. In addition, aircraft are used for hurricane observation and some data are collected from commercial flights to fill in gaps in the observation networks. Aircraft are extensively used for research investigations around thunderstorms or wherever high-density upper-air data are needed.

When selecting a platform, consideration should be given to where the measurement is to be made, whether the platform can be permanently fixed or is moving, cost, and exposure. To some extent, any platform, even a simple tower for surface measurements, interacts with the atmosphere and affects instrument exposure. A simple 10 m tower, shown in fig. 1-2, has a wind sensor at 10 m and temperature and a relative humidity (T&RH) sensor at 1.5 m in addition to a radio antenna for data transmission, a solar panel and battery for power, a barometer, and a data logger. These sensors must be mounted with due consideration for exposure to prevailing winds, to minimize tower effects.

1.3.2 Communication Systems

A communications network is a vital part of almost every meteorological measurement system at all scales. Historically, meteorological communications have relied primarily on land-line and radio links. More recently, polar orbiting and geostationary satellites are used for data communications in macroscale or synoptic measurement systems and even in many mesoscale systems. Commercial satellites are used to broadcast data from central points, with sophisticated uplinks, to users equipped with fairly simple antennas and receivers (inexpensive downlinks).

The ideal communications system would reliably transmit data from the remote instrument platform to a central facility and in the reverse direction with little or no

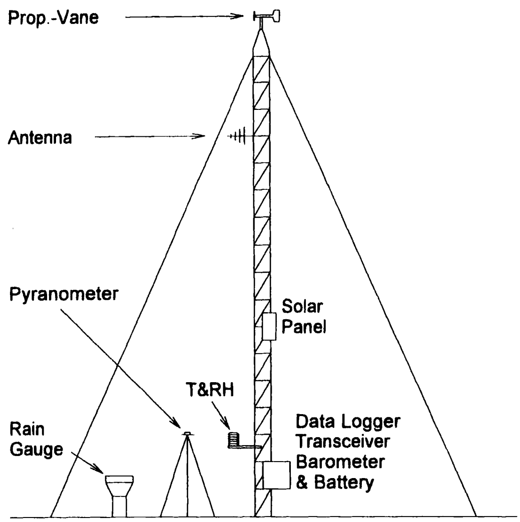

Fig. 1-2 A 10-meter tower for surface measurements.

time delay and without limiting the volume of data to be transmitted. Communication both to and from the remote site is required to synchronize local clocks in the data loggers, to load operating programs into the data loggers, and to make special data requests, to name a few. Two-way communications are not essential but highly desirable.

1.3.2.1 Telephone

Commercial telephone systems provide adequate signal bandwidth, are generally reliable, and cover most land areas. The cost is prohibitive if one must pay for running lines to each station, especially for a short-term project. Even for long-term projects like the Oklahoma Mesonet (Brock et al., 1993) and the ARM Program (Stokes and Schwartz, 1994), phone lines were either avoided entirely or used very sparingly because of the expense involved.

Recent advances in cellular telephone technology coupled with decreasing airtime charges mean that cellular data communications have become a viable alternative to traditional phone lines.

1.3.2.2 Direct Radio

Direct radio links from the remote stations to a central base station are desirable because they offer flexibility, but earth curvature limits line-of-sight links. Figure 1-3 shows the maximum line-of-sight distance between two stations if the remote station antenna is at a height of 10 m. For a base station or repeater antenna height of 200 m, the line-of-sight link is only a little more than 60 km. Direct radio, even

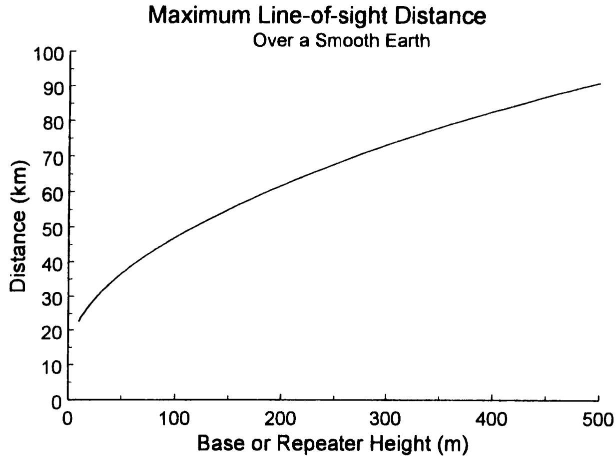

Fig. 1-3 Line-of-sight distance over a smooth earth as a function of height of one end of the link when the other end is fixed at 10 m.

when augmented with repeaters, severely limits the size of a network and causes immense difficulties in complex terrain. For example, if the path of the signal from a remote station to the repeater or to the base station is too close to the ground, the signal could be trapped in an inversion layer and ducted away from the intended destination.

1.3.2.3 Satellite

The first communications satellite that permitted an inexpensive uplink (low power transmitter and simple antenna) was the Geostationary Operational Environmental Satellite (GOES). An inexpensive uplink is essential when a large number of remote stations is involved. In addition, stations may be powered by batteries and solar panels, thereby requiring low-power radio transmitters. As satellite communications technology evolves, communication restraints will be eased, which will lead to vastly improved meteorological networks, especially for the mesoscale.

1.3.3 Power Source

Electrical power consumption of a measurement system is often a vital consideration; the primary concern is cost. Where commercial power is available, cost is not usually a problem. However, many systems are required to be portable or to operate in locations where commercial power is not available. In these cases, the power source is usually batteries, perhaps supplemented with solar panels. Such systems must operate on a severely limited power budget and that constraint affects the selection of components and the overall system design. Battery-powered systems are constrained to select sensors with low power consumption and/or to switch the sensors on only as needed, to conserve power. Heaters generally cannot be used and local computational capability may be severely limited. Therefore, all components must be rated for operation over the expected temperature range.

1.4 Human Aspects of Measurement

Automated instrumentation is used to make measurements that humans cannot, for reasons of safety, cost, or performance (speed or accuracy for example), and the instrumentation must deliver data to the user. Therefore, all measurement systems must be viewed as extensions of the human who wishes to use the data.

1.4.1 Human Perception versus Sensor Measurements

Humans can directly sense a number of variables such as temperature, wind speed and direction, and solar radiation but we have to be calibrated against some standard. We perceive some variables, such as pressure, poorly if at all. In addition, human perception of temperature is affected by wind speed and solar radiation and by humidity in hot weather. Despite all this, the human observer is generally superior to instruments in that we can detect subtle influences and perceive patterns in the weather that would be difficult to discern from the worldview filtered through a measurement system. Humans are superior to instruments for some variables such as precipitation type and reign supreme for visibility that, by definition, is the distance that humans can see objects.

1.4.2 Reasons for Automation

As noted above, the measurement process can be automated with the use of instruments, data loggers, and so on, to perform tasks that humans cannot or will not do.

1.4.2.1 Cost

Very often, a measurement task can be implemented at far lower cost by eliminating people and replacing them with sensors, data loggers, and data communication equipment. Consider a mesoscale network that requires measurement of 10 variables at five-minute intervals 24 hours a day, day after day. Each station would require about five (allowing for shift work, vacations, and sick leave) very dedicated people. Their salary alone would be far more than the cost of the usual equipment.

1.4.2.2 Performance

Instruments can be located in environments hostile to humans and perform tasks difficult or impossible for humans such as recording a number of variables at 0.1

second intervals. In addition, the accuracy of human observations is generally less than that of a well-calibrated and suitably exposed electronic sensor.

1.4.2.3 Eliminating Human Error

We expect instruments to make repetitive measurements with only occasional error. In the same task, a human would be soon bored and, consequently, error prone.

If well done, automation of measurements can reduce costs, improve sensor performance, and reduce human error, but there is a trade-off: the loss of involvement of a human observer. The user of the data may not know what type of sensor was used, how representative its location, magnitude or likelihood of environmentally induced errors, or the response of a sensor to extreme conditions. Automated networks isolate the end user from the sensors and from the people who understand the measurement system.

Automation typically causes a vast increase in the volume of data obtained. Measurements are made more frequently from more sensors in more places. Even with the aid of computers and sophisticated graphics packages it is extremely difficult for a user to examine all of this data and therefore even gross errors may go undetected. Unless automatic data monitoring procedures are implemented for quality control, automation can easily cause a decrease in data quality.

1.4.3 Design, Implementation, and Maintenance of Measurement Systems

While they are important topics, it is beyond the scope of this text to discuss the elements of ergonomic design, or design for easy use and maintenance. The overall measurement system should be designed to facilitate data quality assurance. This could range from local computation and reporting of the standard deviation to installation of redundant sensors.

1.4.4 Interpretation of Sensor Specifications

Reputable vendors offer sensors with a complete set of specifications which can be used to compare sensors from various vendors. What do these specifications tell us about values reported in field use?

EXAMPLE

If the vendor specifies a temperature sensor inaccuracy of 0.2°C, what can one infer about the reported datum of 30°C?

(a) that there is complete certainty that the actual air temperature is 30°C ± 0.2°C?

(b) that there is a 95% probability that the actual air temperature is 30°C ± 0.2°C? (If the errors were randomly distributed in a Gaussian distribution with a standard deviation of 0.1°C)

(c) the probability statement in (b) is OK provided the user can offer reasonable assurances about drift, dynamic error, and exposure error at the time and place of measurement?

Answer (a) cannot be true; it is impossible to put absolute limits on error as that would require testing of all possible input values throughout the sensor range, an infinite task. In practice, if the sensor range is, say, from −30°C to 50°C, the sensor will be tested in a calibration laboratory at a finite number of temperature steps. It might be tested at 17 different temperatures in 5° steps. Setting absolute bounds also requires testing of all sensors. This can be done, but usually at extra cost. Further, one component of error has a random source that manifests itself as irreproducibility: the property that a sensor, when exposed repeatedly to identical conditions, will not produce identical outputs.

Answer (b) could be correct only in the context of a laboratory calibration where conditions are carefully controlled and there is no possibility of drift, dynamic error, or exposure error.

In field conditions, answer (c) is correct. Given a high-quality sensor that has been properly calibrated and a well-designed data acquisition system where the complete system is properly maintained, the largest source of error will be exposure error. This is not included in the vendor specifications because it is a function of many variables that are not under the vendor's control. Exposure error for a temperature sensor is a function of sensor design, radiation shield design, climatology, solar radiation, wind speed and direction, surface reflectivity, and so on. See sect. 3.2 for additional information.

Interpretation of measurements requires involvement of the user, who must judge whether the instrument was properly exposed and whether unusual conditions exist. A measurement that is unusual or unexpected might result from instrument failure or from unusual atmospheric conditions. Sometimes the cause is obvious. If the reported temperature is −273°C, one can reasonably conclude that there has been some kind of instrument failure. The obvious cases should be detected by a data quality assurance system. There will always be some odd data, outliers, that a quality assurance system will pass. The user is the ultimate judge.

1.4.5 Interpretation of Results

Do sensors measure what we want them to measure? A measurement system reports air temperature. Does that mean that the sensor exposure is representative of a large area? That it implies exposure at the WMO standard height somewhere between 1.25 m and 2.0 m? If the data come from a general-purpose mesoscale or synoptic scale measurement system, the presumption is that WMO guidelines have been followed and that the temperature sensor was not installed near a building, a tree, or other obstruction. However, even if WMO guidelines have been followed, either aspirated or unaspirated temperature shields could have been used (see chap. 4). Under certain conditions, shields can induce large errors.

First came the observer who was, at once, the sensor, data acquisition system, and data user. One can sense directly, for example, wind speed and direction and be aware of wind obstacles or shelters that may alter one's perception of the phenomena.

Then came the observer with a hand-held sensor, better equipped to make quantitative measurements if proper operation and calibration of the sensor could be verified. With simple instruments, the observer could readily verify operation and calibration. The observer was still an intimate part of the measurement process. We have progressed to more complicated instruments, powerful data acquisition systems, and communication channels that allow us to monitor measurements made anywhere in the world. But the user of the data may not even know what the sensing instrument looks like or how it is exposed to the atmosphere. The data presentation may not indicate measurement uncertainty. No wonder we find people using terms like "ground truth." Anyone familiar with the measurement process knows that there is no such thing as measurement truth. We can only estimate the variable in question and attempt to quantify the uncertainty.

1.4.6 Human Judgment

Users of the data must ultimately decide to accept, reject, or question the data with or without adequate knowledge for such a judgment. They can be assisted by better instrumentation education, by improved overall measurement system design, and by insisting upon availability of information about system specifications.

1.4.6.1 Instrumentation Education

The objective of a basic instrumentation course is to teach the physics of instruments, the meaning of commonly used instrument performance characteristics and specifications, and the kind of error, especially exposure error, characteristic of each type of instrument. Instrument physics must be the foundation of an instrument course in order to understand the instrument, its fundamental limitations, and how it might be improved.

1.4.6.2 Improved Measurement System Design

The essential first step of any measurement system design is a clear statement of goals. Following this, one must recognize the applicable standards and adhere to them to the extent compatible with the goals. There are standards for instrument exposure, calibration, performance specification, and data acquisition procedures available from ASTM.

If the measurement is meant to be representative of a fairly large area, as in a mesoscale or synoptic observing system, then, for example, the wind measurements should be made at a height of 10 m above level terrain. There should be a clear fetch in all directions with no obstruction closer than 10 times the height of the obstruction. If the purpose of the wind measurement is to characterize flow around a building or in complex terrain, then this standard is not compatible with the goal and there is good reason for not following it. In this case, the goal and the deviation from the standard should be clearly stated so that any user of the data will know what was done and why. This will reduce the chance of misusing the data.

Traditionally, automation of measurement systems has been limited by the technology available at the time of design. Limits have been imposed by the cost of local computer processing power and by communication constraints. As one might expect in times of rapid growth of computer and communication technology, currently available measurement system designs lag far behind technological limits. This growth has been so rapid that even design concepts are lagging. As noted above, the introduction of measurement technology has not been without real tradeoffs: the loss of involvement of the end user with the measurement process and the increased difficulty of maintaining quality assurance. However, technological developments can be, and should be, channeled to help alleviate the problems originally caused by the introduction of technology.

Measurement system design can include the local computation and transmission of derived quantities (standard deviation, and minimum and maximum values in the averaging period, to mention some simple examples) to facilitate improved data quality assurance. In some cases, redundant sensors can be used effectively.

1.5 Quality Assurance

Quality assurance methods and/or final data format may depend on the primary end-user of the data; for instance, will it be used for research or by the general public? For example, relative humidity (RH) sensor inaccuracy specifications allow for the RH reported by the sensor to be in excess of 100% (as high as 103%). A sensor reporting an RH of 102% may be operating correctly but could cause problems for under-informed users. For example, modelers ingesting RH may need to be aware that values greater than 100% are possible and do not necessarily indicate super-saturation conditions. In addition, those unaware of instrument inaccuracy specifications may think the data are incorrect if RH is above 100%.

A more complete data quality assurance program can be developed for a network of stations than for a single measurement station and so this discussion will address the issue of quality assurance for a network. A single station assurance program would be a subset of this.

In designing a measurement system, it is useful to consider the impact of automation on data quality.

Schwartz and Doswell (1991) claim that automation has been accompanied by a decrease in data quality but that this decrease is not inevitable. When a measurement system is automated, some sources of human error are eliminated, such as personal bias and transcription mistakes incurred while reading an instrument, to name only two. However, another, more serious form of error is introduced: the isolation of the observer from the measurement process.

One tends to let computers handle the data under the mistaken assumption that errors are not being made or that they are being controlled. Unless programs are specifically designed to test the data, the computer will process, store, transmit, and display erroneous data just as efficiently as valid data. Automatic transmission of data tends to isolate the end user from the people who understand the instrumentation system. Utilization of computers in a measurement system allows data to be collected with finer time and space resolution. Even if the system is designed to let observers monitor the data, they can be overwhelmed by the sheer volume and unable to effectively determine data quality. Automation, or the use of computers in a measurement system, can have a beneficial impact on data quality if the system is properly designed. Inclusion of data monitoring programs that run in real time with effective graphic displays allows the observer to focus on suspect data and to direct the attention of technicians.

The objective of the data quality assurance (QA) system is to maintain the highest possible data quality in the network. To achieve this goal, data faults must be detected rapidly, corrective action must be initiated in a timely manner, and questionable data must be flagged. The data archive must be designed to include provision for status bits associated with each datum. *The QA system should never alter the data but only set status bits to indicate the probable data quality.* It is probably inevitable that a QA system will flag data that are actually valid but represent unusual or unexpected meteorological conditions. Flagged data are available to qualified users but may not be available for routine operational use.

The major components of a QA program are the design of the measurement system, laboratory calibrations, field intercomparisons, real-time monitoring of the data, documentation, independent reviews, and publication of data quality assessment. Laboratory calibrations are required to screen sensors as they are purchased and to evaluate and recalibrate sensors returned from the field at routine intervals or when a problem has been detected. Field intercomparisons are used to verify performance of sensors in the field since laboratory calibrations, while essential, are not always reliable predictors of field performance. QA software is used to monitor data in real time to detect data faults and unusual events. A variety of tests can be used, from simple range and rate tests to long-term comparisons of data from adjacent stations. Documentation of site characteristics and sensor calibration coefficients and repair history is needed to answer questions about possible data problems.

Independent reviews and periodic publication of data quality are needed since people close to the project tend to develop selective awareness. These aspects of the overall QA program must be established early and enforced by project leaders. The whole QA program should, ideally, be designed before the project starts to collect data.

1.5.1 Laboratory Calibrations

Laboratory calibration facilities are required to verify the calibration of suspect instruments and to obtain a new calibration for instruments that have drifted out of calibration or have been repaired. However, a laboratory calibration is not necessarily a good predictor of an instrument's performance in the field. This is because laboratory calibrations never replicate all field conditions. For example, a laboratory calibration of a temperature sensor would never include the effects of solar and earth radiation, nor would it be subject to poor coupling with the atmosphere due to low wind speeds.

The ultimate calibration tool for wind sensors is a wind tunnel. A good wind tunnel with adequate reference instrumentation to determine the flow speed is an essential tool for establishing a complete calibration of a wind sensor. A far less expensive alternative would be to use simple motor calibration sets provided by the wind sensor vendors. These sets test the anemometer transducer but not the cup wheel or propeller.

Since it is difficult to measure air temperature in the field to 0.1°C, due to radiation error, the laboratory calibration is relatively easy to implement. All that is needed is a temperature transfer standard with errors less than about 0.03°C, a temperature chamber, a bath, and a stirrer. With the temperature standard, it is not necessary to set the chamber to precise temperatures. Nor is it necessary to hold the chamber temperature constant; it is only necessary to control the rate of change of temperature. The rate must be low enough that errors induced by spatial gradients between the temperature standard and the test sensors and the errors induced by the time response of the sensors are small compared to the acceptable error in the sensors.

Rate errors are fairly easy to detect; if the test sensors lag the reference sensor during increasing temperature and lead it when the temperature if falling, the rate of change is too high. The response of the sensors will be a function of the kind of bath and the amount of stirring. The bath also affects spatial gradients. These can be detected by correlating errors with sensor position.

1.5.2 Field Intercomparisons

Two types of field intercomparisons should be performed to help maintain data quality. First, a field intercomparison station should be established and, second, when technicians visit a station, they should carry portable transfer standards and make routine comparison checks.

The field intercomparison station should comprise of operational sensors and a set of reference sensors (higher quality sensors). Both should report data to the base station but the reference station data should be permanently flagged (marked as suspect or otherwise not suitable for operational use).

Portable transfer sensors can be used to make reference measurements each time a technician visits a station. This method can detect drift or other sensor failures that could otherwise go undetected. These sensors can include a barometer and an Assmann psychrometer. In addition, technicians can carry a lap-top computer to read current data, make adjustments to calibration coefficients when sensors are changed, set the data logger clock (if it cannot be set remotely), and reload the data logger program after a power interruption.

1.5.3 Data Monitoring

Neither laboratory calibration nor routine field intercomparisons will provide a real-time indicator of problems in the field. In a system that collects and reports data in real time, bad data will be transmitted to users until detected and flagged. The volume of data flow will likely be far too great to allow human observers to effectively monitor the data quality. Therefore, a real-time, automatic monitoring system is required.

The monitor program should have two major components: scanning algorithms and diagnostic algorithms. The function of the scanning algorithms is to detect outliers while the diagnostic algorithms are used to infer their probable cause. The monitor program can analyze the incoming data stream using statistical techniques adapted from exploratory data analysis, and knowledge of the atmosphere, knowledge of the measurement system, and using objective analysis of groups of stations during suitable atmospheric conditions.

Exploratory data analysis techniques are resistant to outliers and robust, that is, insensitive to the shape of the data's probability density function. Knowledge of the atmosphere allows us to place constraints on the range of some variables such as relative humidity that would be flagged if it were reported greater than approximately 103% (due to sensor inaccuracy specifications). Knowledge of the measurement system places absolute bounds on the range of each variable. If a variable exceeds these limits, a hardware failure may have occurred.

The monitor program must be tailored for the system and should be developed incrementally. Initially, it could employ simple range tests, while more sophisticated tests can be added as they are developed. The QA monitoring program will never be perfect; it will fail to detect some faults and it will label some valid data as potentially faulty. Therefore, *the monitor program must not delete or in any way change data* but set a flag associated with each datum to indicate probable quality. The monitor program should have a mechanism to alert an operator whenever it detects a probable failure. Some of these alerts will be false alarms, that is, not resulting from hardware failure, but may indicate interesting meteorological events.

1.5.4 Documentation

There are several kinds of documentation needed: documentation of individual station characteristics, a station descriptor file, and a sensor database.

Station characteristics can be documented by providing an article describing the station and its instrumentation. In addition, there should be a file of panoramic photographs showing the fetch in all directions and the nature of the land. Aerial photographs can also provide valuable information about a site, as can high-resolution topographical maps.

As part of the system database, a system descriptor file can include the location and elevation of each station and the station type (e.g., standard meteorological station, special purpose agricultural station, or sensor research station).

It is necessary to maintain a central database of sensors and other major components of the system including component serial number, current location, and status. Some sensors have individual calibration coefficients so there must be a method of accounting for sensors to insure that the correct calibration coefficients have been entered into the appropriate data logger. It is also necessary to keep records of how long a component has been in service and where it was used, so that components that suffer frequent failures can be identified. This would help to determine if the component was seriously flawed or if the defect was characteristic of the component design.

This kind of accounting cannot be left to chance; if it is, sensors will inevitably be matched with the wrong calibration coefficients or put back into service without having been repaired or recalibrated. Some sensors require periodic recalibration but it is not feasible to recalibrate them all at once. Therefore, a formal database system should be set up. All technicians should be required to report maintenance activity, including swapping components, and this information should be entered into the database. The database system should be able to generate reports indicating the serial number of every component at a station, the number of components awaiting repair at any given time, the number of spares available, the history of any given sensor or sensor type, etc.

1.5.5 Independent Review

For much the same reason that scientific proposals and papers are reviewed, periodic independent reviews of a network's performance should be invited. It is always possible for people in constant close proximity to a project to become blind to problems and this would help alleviate this.

1.5.6 Publication of Data Quality Assessment

There will be frequent data faults in any network, even with the data quality assurance program outlined above. To assist critics in making a realistic assessment, it would be desirable to publish, periodically, an honest appraisal of the network performance including all data faults, causes when known, and action taken.

1.6 Scope of This Text

In situ or immersion sensors, the subject of this text, are those in direct contact with the atmosphere being measured. Examples are thermometers, anemometers, hygrometers, pressure sensors, rain gauges, etc. Remote sensors monitor the state of the atmosphere at distances great enough to eliminate interaction between the sensor and the parcel of air being sensed. Remote sensors include radars, lidars, sodars, and radiometers.

Sensors discussed in this text include the sensors commonly used in surface networks. Cloud height sensors are included, even though they are remote sensors by the above definition, because they are used in surface synoptic scale networks. There is a brief discussion of radar as used to estimate rainfall in order to contrast this measurement with ordinary rain gauges.

QUESTIONS

1. Define the following terms:

analog signal conditioning
analog-to-digital converter
atmospheric coupling
calibration standards
data quality assurance
digital signal processing
drift error
dynamic characteristics
dynamic error
exposure error
exposure standards
functional model
in-situ or immersion sensors
instrument
measurand
performance standards
primary input
procedural standards
remote sensors
secondary input
sensor

signal
static characteristics
static error
static sensitivity
transducer

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2

Barometry

The objective of barometry is to measure the static pressure exerted by the atmosphere. Static pressure is the force per unit area that would be exerted against any surface in the absence of air motion. It is an isotropic, scalar quantity. Dynamic pressure is the force per unit area due to air motion. It is a vector quantity, following the wind vector. This chapter is concerned with determining the static air pressure and doing so in the presence of air motion (wind) that requires special measurement techniques.

2.1 Atmospheric Pressure

The Earth's atmosphere exerts a pressure on the surface of the Earth equal to the weight of a vertical column of air of unit cross-section. Since air is a fluid, this pressure, or force, is exerted equally in all directions. The static pressure at the surface is given by

$$p(O) = \int_0^\infty g(z)\rho(z)dz \tag{2.1}$$

where $g(z)$ = acceleration due to gravity at height z above sea level in m s^{-2}, and ρ = density as a function of height, kg m^{-3}. The SI unit of pressure is the pascal, abbreviated as Pa. In meteorology, the preferred unit of pressure is the mb or the hPa (equivalent magnitude). Table 2-1 lists some conversion factors for units currently in use in pressure measurement and also for some units no longer favored. Standard sea level pressure in various units is shown in table 2-2.