Chapter 1　Introduction to Meteorological Instruments

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Chapter 1 Introduction to Meteorological Instruments

1.1 Definitions

This section defines terminology related to meteorological instruments.

1.1.1 Instrument Standards

The term "standard" and other similar expressions refer to the various instruments, methods and scales used to establish the uncertainty of measurements. The Guide to Meteorological Instruments and Methods of Observation (CIMO Guide (WMO-No. 8)) provides definitions as follows:

(Measurement) standard: A material measure, measuring instrument, reference material or measuring system intended to define, realize, conserve or reproduce a unit or one or more values of a quantity to serve as a reference

International standard: A standard recognized by an international agreement to serve internationally as the basis for assigning values to other standards of the quantity concerned

National standard: A standard recognized by a national decision to serve, in a country, as the basis for assigning values to other standards of the same quantity

Primary standard: A standard that is designated or widely acknowledged as having the highest meteorological qualities and whose value is accepted without reference to other standards of the same quantity

Secondary standard: A standard whose value is assigned by comparison with a primary standard of the same quantity

Reference standard: A standard, generally having the highest meteorological quality available at a given location or in a given organization, from which the measurements taken there are derived

Working standard: A standard that is used routinely to calibrate or check material measures, measuring instruments or reference materials

Notes:
1. A working standard is usually calibrated against a reference standard.
2. A working standard used routinely to ensure that measurements are being carried out correctly is called a “check standard”.

Transfer standard: A standard used as an intermediary to compare standards

Travelling standard: A standard, sometimes of special construction, intended for transport between different locations

Collective standard: A set of similar material measures or measuring instruments fulfilling, by their combined use, the role of a standard (example: the World Radiometric Reference)

Traceability: A property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties

Calibration: The set of operations which establish, under specified conditions, the relationship between values indicated by a measuring instrument or a measuring system, or values represented by a material measure, and the corresponding known values of a measurand (the physical quantity being measured)

1.1.2 Instrument Accuracy

Terminology related to the accuracy of measurements and the expression of measurement uncertainty is defined here.

True value: A value consistent with the definition of a given particular quantity

Note: This is a value that would be obtained by a perfect measurement. However, true values are by nature indeterminate.

Accuracy of measurement: The closeness of the agreement between the result of a measurement and the true value of the measurand

Note: Accuracy is a qualitative concept.

Repeatability (of measurement results): The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement

Reproducibility (of measurement results): The closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement

Uncertainty (of measurement): A variable associated with the result of a measurement that characterizes the dispersion of values that could be reasonably attributed to the measurand

Error (of measurement): The result of measurement minus the true value of the measurand

Note: Since a true value cannot be determined, in practice a conventional true value is used.

Deviation: The value minus its conventional true value

Random error: The result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions

Notes:
1. Random error is equal to error minus systematic error.
2. Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.

Systematic error: The mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus the true value of the measurand

Notes:
1. Systematic error is equal to error minus random error.
2. Like true value, systematic error and its causes cannot be completely known.

Correction: A value added algebraically to the uncorrected result of a measurement to compensate for systematic error

1.1.3 Instrument Characteristics

Other instrument properties that must be understood when considering accuracy are described here.

Sensitivity: The change in the response of a measuring instrument divided by the corresponding change in the stimulus (see Section 1.2.2.2)

Note: Sensitivity may depend on the value of the stimulus.

Discrimination: The ability of a measuring instrument to respond to small changes in the value of the stimulus

Resolution: A quantitative expression describing the ability of an indicating device to distinguish meaningfully between closely adjacent values of the quantity indicated

Hysteresis: The property of a measuring instrument whereby its response to a given stimulus depends on the sequence of preceding stimuli

Stability (of an instrument): The ability of an instrument to maintain constant meteorological characteristics with time

Drift: The slow variation with time of the meteorological characteristics of a measuring instrument.

Response time: The time interval between the instant at which a stimulus is subjected to a specified abrupt change and the instant at which the response reaches and remains within specified limits around its final steady value (see Section 1.2.2.3)

Lag error: The error that a set of measurements may possess due to the finite response time of the observing instrument

1.2 Fundamentals of Measurement

1.2.1 Measurement Error

The term "measurement" is used to describe the process or result of recording specific values, and may also be called an "observation" in meteorological contexts. Devices used to objectively indicate meteorological variables such as air temperature and precipitation amounts are called "meteorological instruments," or simply "instruments." All measuring instruments can be classified as analogue or digital according to the way they indicate information.

Analogue measuring instruments provide indications in continuous analogue form. The value of the measured variable is read by the observer from a suitably graduated scale.

Digital measuring instruments display the value of the measured quantity in a discrete numerical form as a value on a digital display. This value can be printed out or processed in a computer environment.

All measurements are accompanied by some degree of error. Errors in measurement stem from accumulated discrepancies related to traceability that occur in calibration operations in addition to those caused by observation conditions such as the influence of solar radiation when air temperature is measured. Errors also are classified as either systematic or random according to the processes of their occurrence. If the observer reads out a value from a scale, artificial errors caused by the observer are included.

Systematic errors can sometimes be eliminated through post-measurement correction, and include instrumental errors as well as those that cannot be completely eliminated, such as irregular errors caused by drift due to deterioration of a material's elastic properties or by friction. The level of systematic error can be minimized through regular comparison with or calibration against a reference standard.

Random errors are caused by factors such as noise from the instrument itself, and are difficult to eliminate.

Artificial errors include bias caused by the observer's propensities or carelessness in reading the scale. They can be considerably reduced if the observer takes care in reading measurements.

Although errors in measurement are unavoidable, they should be minimized through regular maintenance, monitoring of observed values and the like.

In addition to these errors, the environment of the observation site also affects observations. This effect is discussed in Section 1.5.4.

1.2.2 Instrument Characteristics

1.2.2.1 Accuracy

As described in the previous section, all measurements are inevitably accompanied by some degree of error. In many cases, the frequency distribution of the difference in the values obtained from an instrument with reference to the true values obtained from a reference standard is as shown in Figure 1.1.

In this figure, T is the true value obtained from the standard, O is the mean value observed with the instrument, and σ_0 is the standard deviation of the values obtained from the instrument under consideration. In this case, the following characteristics apply:

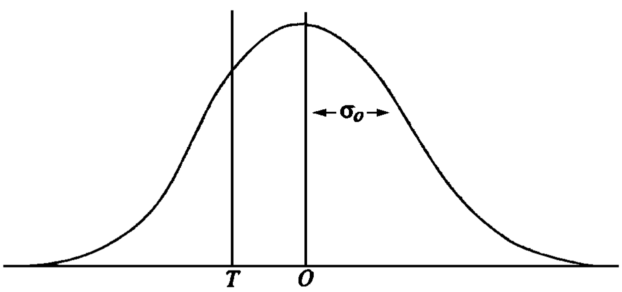

Figure 1.1 Distribution of data in instrument

O – T: systematic error

σ_0 : measurement precision indicating dispersion

The accuracy of this instrument is expressed by (O - T) ± f (σ_0), where f is the probability function. For a series of measurements that would produce an error distribution with standard deviation σ_0, this probability function indicates the likelihood of a value of random error occurring for an arbitrary measurement.

An instrument with a low level of systematic error and dispersion (i.e., low deviation) and high precision is an accurate instrument, which is highly desirable.

Accuracy is a qualitative representation, and its quantitative representation is uncertainty. It is preferable to represent accuracy in terms of uncertainty. In the CIMO Guide, "an accuracy of ± x" is sometimes used, but this should actually read "an uncertainty of ± x at a 95% confidence level."

1.2.2.2 Sensitivity

When a measured value changes in response to a change in the target of measurement, the ratio expressing these changes represents a value called sensitivity. For electric measuring instruments, this corresponds to the ratio of the output signal to the input signal, and is known as the gain. The term "gain" is also used in the same way for general measuring instruments. For example, the sensitivity of a mercury-in-glass thermometer is represented as the ratio of change in the height of the mercury column (output) for a temperature change of 1°C (input). An instrument with a large value for this ratio has high sensitivity.

To facilitate measurement and maximize its accuracy, it is necessary to select an instrument with an appropriate level of sensitivity for the purpose of the measurement. Instruments with high sensitivity tend to have a narrow range of measurement.

1.2.2.3 Response and Time Constant

To measure meteorological variables using an instrument, the surrounding environment and the sensor of the instrument need to be in equilibrium. The temperature of the ambient air, for example, must be the same as the temperature of the mercury in a mercury-in-glass thermometer. If there is a sudden change in the measured quantity, a certain length of time (known as the settling time) is needed to allow a return to equilibrium. This period is called the response time of the instrument.

Meteorological measuring instruments are classified as either first-order or second-order units according to their dynamic behavior during the process through which equilibrium is attained.

The response of simple instruments such as thermometers and hygrometers to a step change

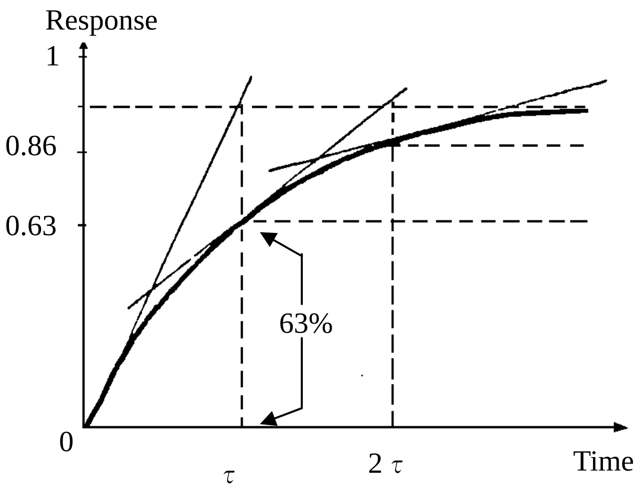

Figure 1.2 Response of a first-order measuring instrument

takes the form shown in Figure 1.2. When a step change is given, the change in output is proportional to the difference between the input (the given forcing function value) and the output. The output approaches the forcing function value rapidly at first, and then gradually. Instruments with such a response are called first-order measuring instruments.

This delay of output in response to input is represented by a time constant (τ in the figure), which is defined as the time taken for the output to reach about 63% of its forcing function value. Approximately 86% of this value is reached by 2τ, and about 99% by 5τ.

The time constant of an anemometer varies almost inversely with wind speed; that is, it is large when the wind speed is low and vice versa. Accordingly, the product of wind speed and the time constant is almost constant, and has a dimension of length known as the response length. The response of an anemometer is represented by the response length.

The definition of the time constant described above is not applied to wind vanes, which oscillate around the direction of airflow before stabilizing. The response of such instruments to a step change in input takes the form shown in Figure 1.3. These instruments are known as second-order units, and their response to a step change oscillates with amplitudes and periods that are functions of the damping ratio (ξ), defined as the ratio of the actual damping of the instrument to the critical damping, which produces no overshoot.

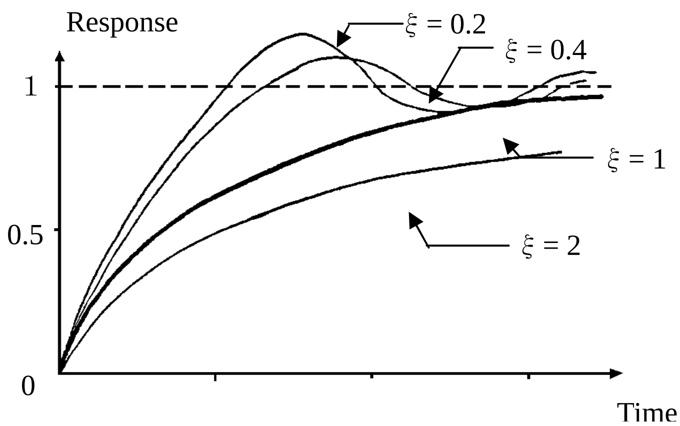

Figure 1.3 Response of a second-order measuring

If ξ is unity, the unit behaves similarly to a first-order measuring instrument; that is, the output approaches its forcing function value rapidly at first and then gradually. If ξ is less than unity, the damping is small (known as underdamping); the output goes beyond the forcing function value and then gradually converges toward it while oscillating around it. The overshoot is small if the value of ξ is close to unity. If ξ is larger than unity, the damping is too strong (known as overdamping); the output approaches the forcing function more slowly, and the response is duller than that in the case of critical damping.

The World Meteorological Organization (WMO) recommends an appropriate damping ratio ξ of between 0.3 and 0.7 so that wind vane overshoot is not excessive but a reasonably short response time is maintained.

It is necessary to select an instrument with an appropriate time constant and damping ratio for the purpose of the measurement. At the same time, there is also a need to determine appropriate methods for processing data such as the sampling interval and the averaging time according to the time constant. It would be pointless, for example, to obtain data with a sampling interval shorter than the time constant of the instrument.

The WMO recommends the use of instruments with a time constant of around 20 seconds and the adoption of an averaging time of more than one minute. Other values are also recommended for the measurement of wind speed; these will be discussed in Chapter 4.

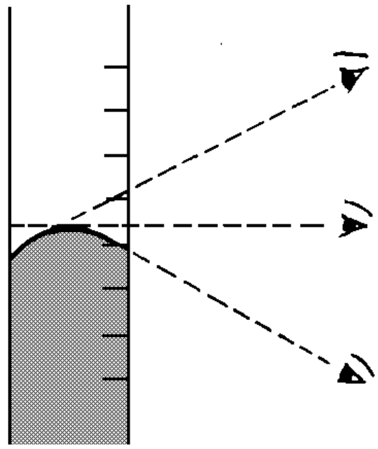
Figure 1.4 Parallax error

1.2.3 Scale Reading

The recent proliferation of automatic instruments has diminished the need for scale readings by observers. However, liquid-in-glass thermometers and precipitation gauges are still widely used, and aspirated psychrometers and mercury barometers are adopted as reference standards. As these instruments have to be read by an observer, a number of points should be kept in mind when making direct readings.

As graduated scales on mercury-in-glass thermometers and mercury barometers stand slightly apart from the mercury column itself, a reading error (known as parallax error) will occur if the observer's eyes are not in the appropriate position, as shown in Figure 1.4; the height of the eyes must be level with the top of the mercury column. In the case of instruments equipped with a mirror on the scale plate (such as aneroid barometers), the observer must read the scale with the eyes in the correct position so that the pointer coincides with its mirror image.

It is sometimes necessary to read down to 1/10 or 1/5 of a scale division. In such cases, errors can occur due to the intervals of scale divisions, the thickness or color of scale marks or observer fatigue. It is also known that reading biases arise as a result of personal propensities. It is therefore important that the observer knows his/her own propensities.

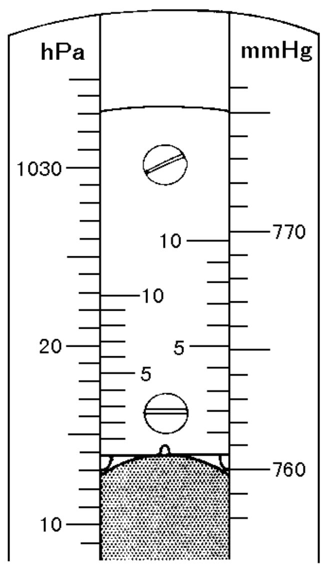

Figure 1.5 A vernier scale

1.2.3.1 Verniers

A vernier scale helps the observer to eliminate errors that may occur in reading tenths of a scale division. Some meteorological instruments (such as Fortin mercury barometers) have a vernier that allows reading to a tenth or a twentieth of the scale division. Verniers are also used in vernier calipers and micrometers.

A vernier scale is divided into 10 or 20 equal parts of 19 divisions of the main scale, or 10 equal parts of 9 divisions of the main scale. When a vernier scale is divided into 10 equal parts of 9 divisions of the main scale as shown Figure 1.5, the relationships governing the length of a single division on the main scale S and that of the vernier scale V are expressed as follows:

$$10V = 9S, \qquad S - V = \frac{1}{10}S.$$

The difference between a division on the main scale and one on the vernier scale is one tenth of a division on the main scale. If the *n*th mark on the vernier scale aligns with a mark on the main scale, the 0 mark on the vernier lies at n/10 of a division of the main scale.

1.3 Accuracy Required for Observation and Sources of Errors

Taking air temperature as an example to discuss how errors arise, sources in individual measurements are as follows:

(a) Errors in international, national and working standards and in comparisons made between them. However, these may be negligible in meteorological applications.

(b) Errors in comparisons made between standards and operational instruments in a climatic chamber or a laboratory. Such errors are small if the operating conditions are appropriate (for example, ± 0.1K uncertainty at a 95% confidence level including the type of errors in (a) above), but can easily become large depending on the skill of the operator and the quality of the facility.

(c) Errors can occur in each measurement due to instrument characteristics; these include errors stemming from incomplete correction for nonlinearity and secular changes due to drift, as well as those caused by fluctuating characteristics of repeatability or reproducibility.

(d) Errors may arise as a result of temperature differences between the air around a thermometer and that within a screen or ventilated shelter. Such errors are small if there is appropriate ventilation, but become large otherwise.

(e) Errors can be caused by sunshine-related temperature differences between the air within a screen or ventilated shelter and the ambient air. Although such errors are small if the screen or ventilated shelter is designed appropriately, the difference in extreme environments may be more than 3°C between ventilated shelters with and without effective sunshine shielding.

(f) Considerable errors may arise if the site is not typical of the surrounding environment, such as if there are heat sources or sinks (e.g., buildings, roads with heavy traffic, land-water boundaries, etc.) nearby.

Of these error sources, (a) to (c) stem from the characteristics of instruments themselves. These types of error must be minimized through appropriate instrument selection and calibration.

The effects of (d) to (f) can be limited if instruments are installed at appropriate sites and operated with care. Otherwise very large errors may arise.

1.4 General Requirements for Instruments

Major requirements for meteorological instruments are accuracy, reliability, convenience of operation and maintenance, simplicity of design and durability.

It is important that the accuracy of an instrument is kept constant over a long period. An instrument whose accuracy is relatively low but can be maintained is better than one with initially high accuracy that deteriorates over time. Accordingly, the following factors should be considered in instrument selection:

(a) An instrument with appropriate accuracy should be selected according to the purpose of the observation. In general, high-accuracy instruments are expensive and difficult to handle.

(b) The instrument's accuracy should be stable over a long period to minimize the need for maintenance work.

(c) It should be easy to identify the sources of errors and eliminate them.

Calibration before instrument installation and after overhaul (including repairs) is necessary to correct observation data and maintain high-accuracy observation.

Most meteorological instruments are in continuous use, meaning that immediate repair or adjustment is not always possible at some sites. Accordingly, a simple, strong structure along with easy operation and maintenance are important factors. A robust structure is especially important for instruments installed outdoors. Although the equipment used for such units may be expensive, they offer better observation results at lower cost in the long run.

1.5 Maintaining Accuracy

1.5.1 Maintenance

Sensors of meteorological instruments (except those of barometers) are installed outdoors, and are exposed to rain, wind and sunshine. Regular maintenance is therefore necessary to achieve stable operation and obtain accurate data. Rain gauges, for example, sometimes become clogged with leaves or dirt, and defective contacts of connectors, water infiltration, strong winds or lightning frequently cause damage to instruments. In addition to regular maintenance, special maintenance also needs to be carried out after unusual stormy events.

Even if an observation environment is favorable at the time of initial installation, changes such as the growth of trees and weeds may change the observation conditions. Accordingly, necessary maintenance such as trimming and mowing during regular inspections should be carried out as appropriate.

An instrument maintenance schedule for regular inspections and part replacement should be drawn up in consideration of the inspection procedures recommended by the manufacturer.

By executing observation data quality control regularly and as frequently as possible at observation sites or data centers where observation data are collected and used, it is possible to detect problems with instruments early.

1.5.2 Comparison and Calibration

Operational instruments should be calibrated before installation against a reference standard in a climatic chamber, a wind tunnel or other such facilities. The results of calibration for correction should be prepared for use at any time for each station.

As the performance and characteristic values of an instrument change gradually over time, regular calibration should be planned. Interim calibration should be carried out in the following cases:

(a) When a change of appearance that may affect instrument performance is recognized
(b) When an instrument is repaired or adjusted
(c) When a systematic error in the observed values is recognized after comparison with other instruments of the same type
(d) When the instrument seems to exhibit a change in performance after inspection

To identify performance changes in operational instruments, on-site comparison with reference standards should be regularly carried out. The comparison interval should be determined by considering the change in performance of each instrument.

1.5.3 Handling of Instruments

This section describes common considerations for the handling of instruments.

1.5.3.1 Handling of Chemical Agents and Other Hazardous Materials

Chemical agents harmful to humans are used in some meteorological instruments as well as in accuracy verification work and maintenance. Such chemicals should be handled and stored according to the relevant instructions and any regulations issued by national authorities. In handling these chemicals, the following precautions should be noted:

(a) All individuals involved in handling should know the chemical properties of the material.
(b) Materials should be kept in well-labeled containers and stored appropriately.

Mercury – an element poisonous to humans – is often used in barometers and thermometers. It is absorbed into the body through the skin in both liquid and gaseous states, and its vapor can be inhaled. A high intake of mercury results in acute poisoning. As mercury accumulates in bones or the tissues of internal organs, even small amounts can cause chronic organ disorders and be fatal in the long term. It is therefore necessary to pay attention to the following points when handling mercury:

(a) The floor of rooms where mercury is stored or used in large amounts should be shielded and laid with an impervious covering. It must not be stored together with other chemicals, especially with ammonia or acetylene.
(b) Mercury has a relatively low boiling point of 357°C, and produces dangerous poisonous gas upon combustion. It must not be stored close to heat sources.
(c) Regular inspections of the room and staff should be carried out when mercury is handled to catch hazardous levels of mercury concentration.

1.5.3.2 Safety of Operation

Most wind vanes, anemometers, radiometers and sunshine recorders are installed in elevated locations to avoid influence from neighboring buildings and other obstacles. In designing poles or towers, footholds for routine inspections and maintenance work should be secured. Workers should be sure to prepare safety belts for these operations.

1.5.3.3 Transportation of Instruments

When a meteorological instrument is moved, it should be handled carefully so that its accuracy is not affected. Details of special considerations for mercury barometers and other instruments are described in the relevant chapters.

(a) Use a special case for transportation if available. Otherwise, a crate or similar container should be prepared. It is preferable to use the instrument container originally provided by the manufacturer. Before transportation, wrap the instrument to protect it from dust and pack with cushions to prevent breakage. Protect thermometer bulbs by placing a corrugated cardboard box around them before packing. Take care to keep the unit upright during transportation. When transporting electronic instruments or precision electrical circuits, take special care to protect them from strong shock or vibration.

(b) Fully unwind the springs of clock-driven recorders. Insert a cushion in the space above the drum-holding knob at the top of the center shaft in order to prevent vertical play of the drum. Remove the pin (with a ring) that connects the lever and the reed, and tie it to the stud. Wipe any ink from the recording pen and keep it away from the recording chart. Tie the pen arm to the pen holding lever. Reinforce the cover glass of the recorder with plywood or similar to prevent breakage.

(c) In addition to these general instructions for transportation, refer to the instructions in the manufacturer’s manual.

1.5.4 Siting and Exposure

1.5.4.1 Metadata

The accuracy of meteorological observation is affected not only by the instrument itself but also by the site, the exposure of the instrument and observation operations. Accordingly, records should be kept at each site outlining the history (metadata) of instruments and observation environments, including details such as the establishment of the observatory, the history of maintenance, calibrations and maintenance, the location of instruments and staff changes. Metadata is especially important for precipitation, wind, air temperature and other observation elements that are sensitive to the location of the instrument.

1.5.4.2 Site Selection

Meteorological observation sites should be established in locations where the observed values of meteorological elements are typical of those in the surrounding area. In general, for most meteorological observations, the site should be free from the influence of natural obstacles and artificial buildings. For precipitation, however, surrounding wind fields have an influence, making sites where obstacles effectively provide shelter from winds in all directions favorable. The environment of an observation site may change over time as trees grow and buildings are constructed nearby. Sites should be located, if possible, in a place where such influences are minimal. However, as it is difficult to find this type of ideal location for observation in most cases, it is also important to understand the influence of the environment on observation elements and to keep the metadata described above to allow evaluation of validity for observed values.

1.5.4.3 Determination of Reference Direction

Wind vanes, propeller anemometers, sunshine recorders and radiometers must be installed in an appropriate direction. As it is easiest to locate in the meridian direction, instruments are generally marked with "north" and "south" so that they may be aligned with the meridian line. Methods to determine the meridian direction are outlined below.

(a) **Method using the position of the sun**. This approach makes use of the sun’s position at the meridian hour. Although the technique provides the correct direction, it requires considerable skill to attain high accuracy, and weather conditions may limit the window of time in which it can be used.

The sun will cause a vertical object to cast a shadow indicating the exact meridian direction at the meridian hour. The longer the shadow of the object, the more easily the meridian direction can be determined, resulting in higher accuracy. Suspending a weight with a thread is the easiest and most accurate way of casting a shadow. In such cases, to keep the weight at rest, it should be ensured that the upper end of the thread is attached firmly and windbreaks are arranged to prevent the weight from swinging.

With a tripod and a conical weight, a line can be drawn by tracing the shadow of the thread at the meridian hour. As it is difficult to draw a meridian line passing through a given point on the stand on which the instrument is mounted, it should first be drawn in an appropriate position, and a line parallel to it should be transferred to the appropriate position.

Since the sun moves at a rate of 15 degrees of longitude per hour, the meridian hour at a specific observation point can be derived by proportionally dividing one hour by the longitude difference between the observation point and the central standard time site of that country. If the observation point lies to the west and the longitude difference is 10 degrees:

Time difference = 60 minutes × (10 degrees/15 degrees) = 40 minutes

The meridian hour at this point is 40 minutes past the standard-time meridian hour.

(b). **Method using a magnetic compass.** This approach is advantageous in that the meridian line can be determined easily and irrespective of weather conditions. However, determination with a compass may involve some error if there are magnetized objects or iron nearby. When measuring, it should be noted that the northern direction indicated by the magnetic needle (magnetic north) deviates from true north (a deviation known as the declination), and this deviation differs from place to place. In Japan, magnetic north deviates from 4 to 10 degrees to the west of true north.

In practice, the measurer should stand to the magnetic south of the instrument and move an angular distance equal to the declination so that the instrument comes to a position distanced by the declination from magnetic north. A line can then be drawn from the measurer's position to the position of the instrument. This is the meridian line for the instrument.

(c). **Method using a map**. This is the simplest approach to determining the direction, and involves locating a landmark at true north or south on the map. If there are no good landmarks in these directions on the map, several other landmarks can be used and their respective azimuth angles (the angle from true north) can be derived from the map. North can be determined from these azimuth angles using a theodolite or the like.

On vernal and autumnal equinox days, the sun rises and sets in the true east and true west, meaning that ground objects can be used if they are photographed or sketched.

1.5.5 Procedure for Instrument Replacement

The influence of instrument replacement on measured values should be minimized. Accordingly, the difference in performance between the new instrument and the current one should be checked in a laboratory. If the new instrument has different characteristics, the change in observed values after replacement may be mistaken as a change in the climate around the observation site. In order to evaluate this change, the new and current instruments should be compared for at least a year before the current one is taken out of service.

Similarly, if the observation site is to be changed, it is preferable to carry out observations at both the new and old sites and compare the results.

1.5.6 Approach to Observation

Unlike physical experiments performed in laboratory environments, it is impossible to repeat meteorological observations carried out in natural conditions. Observers should therefore try to fully understand the operational conditions of their instruments and observation environments.

The use of automatic observations has recently increased, and we are apt to quickly accept indicated or recorded data. However, unlike communication apparatus and other equipment, stable operation cannot always be expected from meteorological instruments, and incorrect values are sometimes indicated. Observers should keep in mind that no instrument is perfect and pay careful attention to weather changes and data at neighboring observation sites. It is important to detect instrument faults as soon as possible.