CHAPTER CONTENTS

Page

CHAPTER 1. MEASUREMENTS AT AUTOMATIC WEATHER STATIONS 526
1.1 General 526
  1.1.1 Definition 526
  1.1.2 Purpose 526
  1.1.3 Meteorological requirements 526
  1.1.4 Climatological requirements 528
  1.1.5 Types of automatic weather stations 529
  1.1.6 Networking 529
1.2 Automatic weather station hardware 530
  1.2.1 Sensors 530
  1.2.2 Central processing unit 533
    1.2.2.1 Data acquisition 534
    1.2.2.2 Data processing 536
    1.2.2.3 Data transmission 536
  1.2.3 Peripheral equipment 536
1.3 Automatic weather station software 537
  1.3.1 System software 538
  1.3.2 Application software 538
    1.3.2.1 Initialization 538
    1.3.2.2 Sampling and filtering 539
    1.3.2.3 Raw-data conversion 539
    1.3.2.4 Instantaneous meteorological values 540
    1.3.2.5 Manual entry of observations 540
    1.3.2.6 Data reduction 540
    1.3.2.7 Message coding 541
    1.3.2.8 Quality control 541
    1.3.2.9 Data storage 543
    1.3.2.10 Data transmission 543
    1.3.2.11 Maintenance and calibration 545
    1.3.2.12 Data display 545
1.4 Automatic weather station siting considerations 546
1.5 Central network data processing 546
  1.5.1 Composition 546
  1.5.2 Quality management of network data 547
1.6 Maintenance 547
1.7 Calibration 549
1.8 Training 550

REFERENCES AND FURTHER READING 551

CHAPTER 1. MEASUREMENTS AT AUTOMATIC WEATHER STATIONS

1.1 GENERAL

1.1.1 Definition

An automatic weather station (AWS) is defined as a "meteorological station at which observations are made and transmitted automatically" (WMO, 1992*a*).

At an AWS, the instrument measurements are read out or received by a central data-acquisition unit. The collected data from the autonomous measuring devices can be processed locally at the AWS or elsewhere, for example, at the central processor of the network (WMO, 2010*a*). Automatic weather stations may be designed as an integrated concept of various measuring devices in combination with the data-acquisition and processing units. Such a combined system of instruments, interfaces and processing and transmission units is usually called an automated weather observing system (AWOS) or automated surface observing system (ASOS). It has become common practice to refer to such a system as an AWS, although it is not a "station" fully in line with the stated definition. Nevertheless, throughout this chapter, an AWS may refer to just such a system.

1.1.2 Purpose

Automatic weather stations are used for increasing the number and reliability of surface observations. They achieve this by:

(a) Increasing the density of an existing network by providing data from new sites and from sites that are difficult to access and inhospitable;

(b) Supplying, for manned stations, data outside the normal working hours;

(c) Increasing the reliability of measurements by using sophisticated technology and modern, digital measurement techniques;

(d) Ensuring the homogeneity of networks by standardizing the measuring techniques;

(e) Satisfying new observational needs and requirements;

(f) Reducing human errors;

(g) Lowering operational costs by reducing the number of observers;

(h) Measuring and reporting with high frequency or continuously.

1.1.3 Meteorological requirements

The general requirements, types, location and composition, frequency and timing of observations are described in WMO (2010*b*, 2011*c*).

Considering that AWSs are fully accepted as meteorological stations when providing data with accuracy comparable to that of conventional stations, the accuracy requirements given in Part I, Chapter 1 of the Guide may also be applied, as appropriate, to AWSs.

The guidance provided in this chapter must be used in conjunction with the chapters on measurements of the various meteorological variables in Part I and, in particular, with the chapters on quality management (Chapter 1), sampling (Chapter 2) and data reduction (Chapter 3) in Part IV.

The development and installation of AWSs should be the result of a definite, coordinated plan for getting data to users in the format required. To achieve this, negotiations should first be undertaken with the users to draw up a list of all functional requirements and to develop practical means of fulfilling them.

Furthermore, it is not always satisfactory to rely on equipment suppliers to determine operational requirements. The Commission for Instruments and Methods of Observation (CIMO) gives the following advice to Members of WMO and, by inference, to any Service taking meteorological measurements.

When considering the introduction of new AWS instrument systems, Meteorological Services should:

(a) Introduce into service only those systems that are sufficiently well documented so as to provide adequate knowledge and understanding of their capabilities, characteristics and any algorithms used;[1]

(b) Retain or develop sufficient technical expertise to enable them to specify system requirements and to assess the appropriateness of the capabilities and characteristics of such systems and algorithms used therein;[2]

(c) Explore fully user requirements and engage users in system design of AWSs;

(d) Engage users in validation and evaluation of the new automated systems;

(e) Engage manufacturers in the system assessment and need for improvements in performance;

(f) Develop detailed guides and documentation on the systems to support all users;

(g) Develop adequate programmes for maintenance and calibration support of the AWSs;

(h) Consult and cooperate with users, such as aeronautical authorities, throughout the process from AWS design, to implementation, to operational use;

(i) Develop and apply reporting methods for national use to accommodate both observations generated by traditional and automated systems.

With respect to the automation of traditional visual and subjective observations, and future changes in reporting code, Meteorological Services should improve their definition of requirements with respect to:[3]

(a) Areas of application for which data are no longer required;

(b) Areas of application for which different or new data are needed;

(c) Prioritizing the requirements for data to be provided by AWSs.

---

[1] Recommended by the Commission for Instruments and Methods of Observation at its twelfth session (1998) through Recommendation 2 (CIMO-XII).

[2] Recommended by the Commission for Instruments and Methods of Observation at its twelfth session (1998) through Recommendation 2 (CIMO-XII).

[3] Recommended by the Commission for Instruments and Methods of Observation at its twelfth session (1998) through Recommendation 5 (CIMO-XII).

When considering the development and application of algorithms for AWSs, Meteorological Services should:[4]

(a) Encourage instrument and system designers to work closely with relevant users to understand fully user requirements and concerns;

(b) Work together with system designers to publish and disseminate, for widespread use and possible standardization, descriptions of the data-processing algorithms used in their systems to derive meteorological variables;

(c) Test and evaluate thoroughly new algorithms and systems being introduced and disseminate the test results in the form of performance characteristics to users of the observations;

(d) Evaluate thoroughly, through field testing and intercomparison, the relationship of new algorithms and systems to previous methods, and establish transfer functions for use in providing data continuity and homogeneity, and disseminate these data to users.

1.1.4 **Climatological requirements**[5]

Where a proposed automatic station has a role in providing data for climatological records, it is important for the integrity, homogeneity and utility of the climate datasets that the following areas be considered for action (see WMO, 1993):

(a) In cases where an AWS replaces a manual observing system that has been in operation for a long time, a sufficient overlap in observation systems to facilitate maintaining the homogeneity of the historical record must be assured.[6] The overlap time is dependent on the different measured variables and on the climate region. In tropical regions and islands, the overlap time could be shorter than in extratropical and mountainous regions. The following general guidelines are suggested for a sufficient operational overlap between existing and new automated systems:

    (i) Wind speed and direction: 12 months

    (ii) Temperature, humidity, sunshine, evaporation: 24 months

    (iii) Precipitation: 60 months

    (It will often be advantageous to have an ombrometer operated in parallel with the automatic raingauge.)

    A useful compromise would be an overlap period of 24 months (i.e. two seasonal cycles);

(b) Accurate metadata should be maintained for each AWS installation;[7]

(c) Procedures should be standardized for quality assurance and processing of data from AWSs (see section 1.3.2.8);

(d) The existing and future requirements of climate data users should be defined precisely and considered in developing statements of requirement for automated observations by AWSs;[8]

---

[4] Recommended by the Commission for Instruments and Methods of Observation at its twelfth session (1998) through Recommendation 2 (CIMO-XII).

[5] Recommended by the Commission for Instruments and Methods of Observation at its twelfth session (1998) through Recommendation 3 (CIMO-XII).

[6] Note also WMO (2010*a*), section 3.2.1.4.4.4(c) "one year of parallel measurements does not suffice; preference is given to at least two years, depending on the climatic region".

[7] See Part I, Chapter 1, section 1.1.3.

[8] See Part I, Chapter 1, Annex 1.E.

(e) Climate users should be trained in the most effective use of AWS data;[9]

(f) Specifications for a standardized climatological AWS should be developed which would record a basic set of climate variables such as temperature, precipitation, pressure and wind. Standardized water vapour measurements should be included due to the significance of this parameter in climate-change studies. Extreme values of all variables should be accurately and consistently recorded in a way that can be precisely related to older, manually-observed, data.[10]

1.1.5 **Types of automatic weather stations**

Automatic weather stations are used to satisfy several needs, ranging from a simple aid-to-the-observer at manned stations to complete replacement of observers at fully automatic stations. It is possible to classify AWSs into a number of functional groups; these frequently overlap each other, however, and the classification then begins to break down. A general classification could include stations that provide data in real time and those that record data for non-real-time or off-line analysis. It is not unusual, however, for both of these functions to be discharged by the same AWS.

Real-time AWS: A station providing data to users of meteorological observations in real time, typically at programmed times, but also in emergency conditions or upon external request. Typical real-time use of an AWS is the provision of synoptic data and the monitoring of critical warning states such as storms and river or tide levels.

Off-line AWS: A station recording data on site on internal or external data storage devices possibly combined with a display of actual data. The intervention of an observer is required to send stored data to the remote data user. Typical stations are climatological and simple aid-to-the-observer stations.

Both types of stations can optionally be set up with means both for manual entry and for the editing of visual or subjective observations that cannot yet be made fully automatically. This includes present and past weather or observations that involve high costs, such as cloud height and visibility. Such a station could be described as partially or semi-automated.

Since AWSs can be very expensive, the stations' facilities can also be used to satisfy the common and specific needs and requirements of several applications, such as synoptic, aeronautical and agricultural meteorology, hydrology and climatology. They may also be used for special purposes, such as nuclear power safety, air and water quality, and road meteorology. Some AWSs are, therefore, multipurpose AWSs.

1.1.6 **Networking**

An AWS usually forms part of a network of meteorological stations, each transmitting its processed data to a central network processing system by various data transmission means. As the tasks to be executed by this central system are strongly related, and often complementary, to the tasks of the AWSs, the functional and technical requirements of both the central system and the AWSs should be very well coordinated.

When planning the installation and operation of a network of AWSs, it is of the utmost importance to consider the various problems associated with maintenance and calibration facilities, their organization and the training and education of technical staff. Network density considerations are beyond the scope of this Guide as they depend on the specific applications. However, the optimum siting and exposure of stations have an important influence on the performance of the stations and must be studied before they are installed.

---

[9] For example, see WMO (1997), especially Part II – "Implementation and user training considerations".

[10] Ibid.

1.2 AUTOMATIC WEATHER STATION HARDWARE

An AWS may consist of an integrated AWOS (and data-acquisition system) or a set of autonomous measuring devices connected to a data-collection and transmission unit. The layout of an AWS typically consists of the following:

(a) On a standard observing area, preferably no smaller than 25 m x 25 m (Part I, Chapter 1, and WMO, 2010*a*), a series of automated sensors sited at the recommended positions and interconnected to one or more data collection units using interfaces, or for an AWOS, a set of sensors installed in close combination, but not affecting each other, directly connected to a central processing unit (CPU) by means of shielded cables, fibre optics, or radio links;

(b) A CPU for sensor data-acquisition and conversion into a computer-readable format, proper processing of data by means of a microprocessor-based system in accordance with specified algorithms, the temporary storage of processed data, and their transmission to remote users of meteorological information;

(c) Peripheral equipment such as a stabilized power supply providing power to the various parts of the station, a real-time clock, and built-in test equipment for automatic monitoring of the status of vital parts of the station. For specific applications, local terminals for the manual entry and editing of data, display devices and printers, or recorders are added to the station.

The growing interaction between society and the atmosphere results in changing and growing requirements, such as demands for more stations and more variables to be measured, transmission at more frequent intervals, new formats and better performance. As a consequence, existing AWS hardware and software have to be adapted to new requirements. This can be carried out only if the AWS is well planned on a modular basis. Adaptation processes and tests are often more complicated than expected. A well-planned AWS includes pre-tested options that allow changes in the configuration and the system parameters. Other desirable features include spare power capacity, space in installation frames, spare communication interfaces, spare processing capacity and a flexible software environment. Guidance on preparing a functional specification for the AWS system is available in Part I of WMO (1997).

1.2.1 Sensors

The meteorological requirements for sensors used at AWSs are not very different from those of sensors at manual observation stations. See also the recommendations in the relevant chapters in Part I of this Guide. Because measurements at most AWSs are controlled from long distances, these sensors must be robust, fairly maintenance-free and should have no intrinsic bias or uncertainty in the way in which they sample the variables to be measured. In general, all sensors with an electrical output are suitable. A large number of sensors of varying performance and quality (and price) are suitable for use with automatic data-acquisition systems. There are frequent new developments, some enhancing the performance of existing sensors, while others are often based on new physical principles. Depending on their output characteristics, sensors can be classified as analogue, digital and “intelligent” sensors.

Analogue sensors: Sensor output is commonly in the form of voltage, current, charge, resistance or capacitance. Signal conditioning converts these basic signals into voltage signals.

Digital sensors: Sensors with digital signal outputs with information contained in a bit or group of bits, and sensors with pulse or frequency output.

“Intelligent” sensors/transducers: Sensors including a microprocessor performing basic data-acquisition and processing functions and providing an output in serial digital or parallel form.

With regard to meteorological sensors, Part I of this Guide gives a full description of general aspects, types of sensors, methods of measurement, units, scales, exposure, sources of error, calibration and maintenance. CIMO assists Members through the regular organization of international instrument intercomparisons. The results can be very valuable for evaluating different measuring approaches. Since 1968, CIMO has been using questionnaires to obtain information on instrument development, and a report, entitled the *Instrument Development Inquiry*, is published every four years. The reports contain information on both instruments under development and instruments put into operational use. Information on new developments and operational experience can be found in the proceedings of national symposiums, magazines and journals, and also in the proceedings of the technical conferences organized regularly by CIMO. These technical conferences are accompanied by an exhibition of meteorological instrumentation where manufacturers present their latest developments. The results of CIMO intercomparisons, the *Instrument Development Inquiry* reports and the proceedings of CIMO technical conferences are published by WMO in the Instruments and Observing Methods reports series. The direct exchange of experience between operators of AWS networks, in particular those operating stations in similar environmental conditions, is recommended as another way of obtaining information.

Some specific considerations concerning AWS sensors are given in the following paragraphs. Achievable operational accuracies are given in Part I, Chapter 1, Annex 1.E[11] of the Guide. As experimental results become available, these estimates will be updated by CIMO, as appropriate. Sensor (laboratory) calibration accuracy should be better by a factor of at least two allowing for transformation to linear response functions. Sensor resolution should be better by a factor of about three than the stated requirement (which includes the performance of the interface).

Atmospheric pressure: A wide variety of devices exists, mostly based upon the use of an aneroid capsule, vibrating wire, or quartz crystal which provide an output in electrical analogue or digital form. For digital sensors, reference is made to WMO (1992*b*). The main problems to be carefully considered by the designer or specifier of an AWS are the adverse effects of temperature, long-term drift, vibration and exposure. Temperature effects are severe and are not always fully compensated by built-in temperature compensation circuits. AWS pressure sensors have an intrinsic long-term drift in accuracy, typically less than 0.2 to 0.3 hPa every six months, and therefore require regular calibration. The effects of vibration and mechanical shocks on the output of pressure sensors are important, especially where marine AWS applications are concerned. Because of the vulnerability of most readily available pressure sensors to the effects of external exposure, it is common practice to house the pressure instrument within a sealed and thermo-stabilized small box inside the CPU enclosure. In some countries, the sensor is connected to the outside of the box via a tube equipped with a static pressure head. For aeronautical applications or at remote stations, where a high degree of accuracy and reliability are required, two or more pressure sensors are incorporated in the station.

Part I, Chapter 3 gives guidelines on the use of digital barometers with AWSs.

Temperature: The most common types of thermometers used in an AWS are pure metal resistance thermometers or thermistors. The platinum resistance thermometer (100 Ω at 0 °C) shows very good long-term stability and can be considered as the preferred type of sensor.

Electrical thermometers usually have a short time-constant and, when sampled by fast electronic circuits, their output reflects high-frequency low amplitude fluctuations of the local temperature. This problem can be avoided by using sensors with a long time-constant, by artificially damping the response with a suitable circuit to increase the time constant of the output signal, or by averaging digitally the sampled outputs in the CPU. Resistance thermometers require linearization. This can be obtained by appropriate circuits in signal conditioning modules, or by software algorithms. It is highly recommended that the thermistor characteristics should be linearized. Of great concern is the proper protection of the sensor against the effects of radiation. Radiation shields adjusted to the size of the sensor are widely used and replace the common naturally ventilated Stevenson screen in an AWS. For accurate measurements, the radiation shields should be artificially ventilated with an air speed of about 3 m s^{-1}, but precautions should be taken to prevent the entry of aerosols and drizzle in order to avoid wet-bulb effects.

---

[11] As specified by the Meeting of Experts on Operational Accuracy Requirements (1991) and approved by the forty-fourth session of the Executive Council (1992) for inclusion in this Guide.

Humidity: A very comprehensive overview of humidity sensors for use in an AWS can be found in WMO (1989*a*).

Although relatively low-cost resistance and capacitive sensors for direct relative humidity measurements are widely employed in AWSs, they are still susceptible to poor performance in the presence of pollutants and require special protection filters. Intercomparisons reveal that additional corrections have to be applied for measurements below 0 °C, even if the sensors incorporate temperature compensation circuits and if hysteresis problems occur when exposed to saturated conditions.

Dewpoint meters, such as the saturated lithium chloride sensor and the chilled-mirror sensor, are also used in an AWS. The major drawback of lithium chloride sensors is their sensitivity to power failures; they require field interventions after a power interruption. The optical dewpoint meter is considered as the most promising technique, but further investigations are required in order to develop a good automatic mirror-cleaning device.

The problems associated with the short time-constant of many humidity sensors are more critical than for temperature sensors. As for temperature measurements, all types of sensors have to be installed in proper radiation shields. Preference should be given to aspirated or well-ventilated radiation shields. Shields may be similar in construction to those used for temperature measurements. Large errors can occur due to aspiration and cleaning problems.

Wind: The use of conventional cup or propeller anemometers with pulse or frequency output is widespread and presents no particular technical problem other than that associated with icing in severe conditions. This complication can be overcome by heating the sensor in moderate icing conditions, but this results in a significant increase in electrical power consumption. It is recommended that, for new cup and propeller anemometers, the response length should be smaller than 5 m and that, in new digital systems, the sampling frequency must be compatible with the filtering applied. In counting devices, this implies that the number of pulses over one counting interval is considered as one sample.

The use of conventional analogue instruments equipped with a potentiometer for wind direction measurements is also widespread in AWSs. Wind-vane devices with digital angle encoders, usually in one or other form of Gray code, are increasingly used. Wind vanes with an undamped natural response length smaller than 10 m and a damping ratio between 0.3 and 0.7 are recommended. For vanes with digital encoders, a minimum resolution of 7 bits is required.

CIMO also recommends that, for new systems, it should be possible to report standard deviations of wind speed and direction with a resolution of 0.1 m s^{-1} and 10°, respectively.

A wind system with a serial digital output and one or more digital displays providing a direct visualization of the operational variables (wind peak, wind averages over two and 10 min, wind direction and extremes) is a typical example of an intelligent sensor.

Precipitation: The most common rainfall-measuring equipment in an AWS is the tipping-bucket raingauge. Gauges are rapidly clogged by debris such as leaves, sand or bird droppings; therefore, care must be taken with AWSs used for long unattended operations. For measurements of rain and snowfall below 0 °C, different parts of the gauge must be heated properly. This can give rise to serious electrical power problems, in particular for battery-operated AWSs. Care should be taken since heated gauges introduce errors due to evaporation losses. An achievable observing accuracy of 5% to 10% is considered to be excellent. Accuracy can be improved by surrounding the raingauge with a proper windshield (for example, a Nipher shield) (see WMO, 1994, for a comparison of precipitation sensors).

Sunshine: A number of sunshine duration recorders with electrical output are available. Reference is made to WMO (1989*b*). WMO has adopted a threshold value of 120 W m^{-2} for bright sunshine of direct solar irradiance, thus solving a long-term problem. A drawback of a sunshine sensor for unattended use over long periods of time is that dirt accumulates on the front aperture which results in apparent changes in threshold.

Radiation: Most of the sensors used for these measurements at conventional stations can, in principle, be connected to an automatic system. The main technical problem is that these sensors are usually analogue devices that produce very small, continuously variable voltages as signal output. These voltages are very vulnerable to electromagnetic interference on the signal cables and adequate measurements have to be taken. The problem of contamination of the front aperture is even more severe for radiation measurements (which are absolute measurements) than for bright sunshine. Dust deposits on uncleaned pyranometer domes are considered to give a 2% loss of accuracy (excluding days with frost and dew). As a result, the effective use of radiation instruments at sites that are unattended for several days is hard to envisage. An achievable observing accuracy (daily mean) is of the order of 5%.

Cloud height: The measurement of cloud height at an AWS is now mostly accomplished with the aid of (laser) ceilometers. Reference is made to WMO (1988) for an evaluation of current systems. Difficulties are still experienced in processing automatically the signals from the sensors in order to produce accurate measurements of cloud-base height under the wide range of conditions encountered in nature, in particular rain and snow. Another difficulty is that the sensors sample the cloud height only over a very small area of sky directly above the detector. When provided to a remote user, such information can present a dangerously incorrect picture of the state or coverage of the sky, especially if the data are to be used for aviation purposes. This may be overcome by the use of algorithms to estimate cloud cover during a 30 min processing interval. In some countries, the role of the ceilometer is, however, that of an aid to the observer who is watching the sky. Ceilometers normally require a significant amount of electrical power and cannot generally be used unless a conventional supply is available. Furthermore, their performance may be reduced or distorted by the accumulation of snow, dust or other forms of contamination on the window of the exit and front apertures of the optical or infrared beam.

Visibility: A wide variety of instruments is readily available for making visibility measurements at AWSs. Refer to WMO (1990).

A distinction can be made between transmissometers and visibility meters. High accuracy transmissometers are mostly used at airports, while lower accuracy (and less expensive) backward, forward or integrated visibility meters are more common for other AWSs. Both types are available in versions which can be battery-powered and which can, therefore, be used at remote sites where primary alternating current or "mains" power is not available. However, they consume a considerable amount of electrical power and, unless supported by an auxiliary power source, it is not normally feasible to operate them for more than a few weeks without battery changes.

1.2.2 **Central processing unit**

The core of an AWS is its CPU. Its hardware configuration depends on the complexity and magnitude of the functions it has to perform and on whether a unique hardware solution exists. In general, the main functions of the CPU are data acquisition, data processing, data storage and data transmission.

In the majority of existing AWSs, all of these functions are carried out by one microprocessor-based system installed in a weather-proof enclosure as close as possible to the sensors, or at some local indoor location. If the unit is located near the sensors, on-site processing reduces the amount of data which must be transmitted and enables those data to be presented in a form suitable for direct connection to communication channels. In such cases, however, the CPU is vulnerable to power-supply failure and must be protected against the outdoor environment in which it must operate. If the unit can be located indoors, it can usually be connected to a mains supply and operated as if it were located in a normal office environment. However, such a configuration results in an increased number of long signal cables and appropriate signal conditioners.

Depending on local circumstances and requirements, the different functions of the CPU may also be executed by different units. In such cases, each unit has its own microprocessor and relevant software, can be installed at different places in the station, and can communicate with each other through well-established inter-processor data transfer links and procedures. They operate in a dependency relation, the data-processing unit being the independent unit. An example is the installation of one or more data-acquisition units in the field close to the sensors that are connected to the data processing or transmission unit of the CPU by means of one or more telephone lines using digital data transmission. These units can consist of one sensor (for example, an intelligent sensor such as a laser ceilometer), a number of similar sensors (for example, thermometers), or a number of different sensors.

The rapid technological evolution of modern industrial data-acquisition and process-control systems opens up new possibilities for meteorological applications. The high degree of input/output modulation and flexibility, the drastically increased operating speed of microprocessors and, in particular, the availability of dedicated data-acquisition, process-control and telecommunications software make it possible to develop AWSs which can meet the diverse observation needs and requirements of various users. As a consequence, any description of an AWS can be soon out of date and has to be considered with reservation. With this in mind, the following paragraphs give a general idea of the state of the art.

1.2.2.1 ***Data acquisition***

In general, the data-acquisition hardware is composed of:

(a) Signal-conditioning hardware for preventing unwanted external sources of interference from influencing the raw sensor signals, for protecting the CPU electronics, and for adapting signals to make them suitable for further data processing;

(b) Data-acquisition electronics with analogue and digital input channels and ports, scanning equipment and data conversion equipment to enter the signals into the CPU memory.

Signal conditioning

Signal conditioning is a vital function in the data-acquisition process and starts with the proper selection of cables and connectors for connecting the sensor to the data-acquisition electronics. It is further accomplished by means of different hardware modules. Taken over from industrial process control, several conditioning functions are now integrated into one removable module. The most convenient and, hence, most common location for installing these modules is on the terminal panels of sensor cables in the same waterproof enclosure as the data-acquisition electronics. Depending on the sensor and local circumstances, various signal-conditioning techniques are available.

Sensor cables: Electrical signals from the sensors entering a data-acquisition system might include unwanted noise. Whether this noise is troublesome depends upon the signal-to-noise ratio and the specific application. Digital signals are relatively immune to noise because of their discrete (and high-level) nature. In contrast, analogue signals are directly influenced by relatively low-level disturbances. The major noise transfer mechanisms include capacitive and inductive coupling. A method of reducing errors due to capacitive coupling is to employ shielded cables for which a conductive material (at ground potential) is placed between the signal cables and the interference source. The additional use of a pair of wires that are entwined is effective in reducing electromagnetic coupling.

Surge protection: When an AWS could be subject to unintentional high-voltage inputs, the installation of a protection mechanism is indispensable to avoid possible destruction of the equipment. High-voltage input can be induced from magnetic fields, static electricity and, especially, from lightning.

Two-wire transmitters: It is sometimes desirable to pre-amplify low-level signals close to the sensor to maintain a maximum signal-to-noise ratio. One way of performing this kind of signal conditioning is to use a two-wire transmitter. These transmitters not only amplify the input signal, but also provide isolation and conversion to a high-current level (typically 4 to 20 mA). Current transmission allows signals to be sent to a distance of up to about 1 500 m.

Digital isolation: Electrical modules are used to acquire digital input signals while breaking the galvanic connection between the signal source and the measuring equipment. The modules not only isolate, but also convert the inputs into standard voltage levels that can be read by the data-acquisition equipment.

Analogue isolation: Analogue isolation modules are used to protect equipment from contact with high voltages, the breaking of ground loops and the removal of large common-mode signals. Three types of analogue isolation are in wide use today: the low-cost capacitive coupling or "flying capacitor", the good performance and moderate cost optical coupling, and the high-isolation and accurate, but higher-cost, transformer coupling.

Low-pass filtering: Filters are used to separate desired signals from undesirable signals. Undesirable signals are noise, alternating current line frequency pick-up, radio or television station interference, and signal frequencies above half the sampling frequency. Generally, a low-pass filter is employed to control these unwanted sources of error, excluding that portion of the frequency spectrum where desired signals do not exist.

Amplifiers: Analogue sensor signals can vary in amplitude over a wide range. The analogue-to-digital (A/D) converter, however, requires a high-level signal in order to perform best. In many cases, an amplifier module is used to boost possible low-level signals to the desired amplitude. Amplifier modules are also employed to standardize the voltage output of all sensors to a common voltage, for example 0–5 voltage direct current.

Resistances: Special modules are used to convert resistances, such as platinum thermometers, into a linearized output voltage signal and to provide the necessary output current for this conversion. It should be noted that the conversion to a linear signal can introduce inaccuracies, which can be critical for some applications.

Data-acquisition function

The data-acquisition function consists of scanning the output of sensors or sensor-conditioning modules at a predetermined rate, and translating the signals into a computer-readable format.

To accommodate the different types of meteorological sensors, the hardware for this function is composed of different types of input/output channels, covering the possible electrical output characteristics of sensors or signal-conditioning modules. The total number of channels of each type depends on the output characteristics of the sensors and is determined by the type of application.

Analogue inputs: The number of analogue channels is usually between 4 and 32. In general, a basic configuration can be extended by additional modules that provide more input channels. Analogue input channels are of particular significance as most of the commonly used meteorological sensors, such as temperature, pressure and humidity sensors, deliver a voltage signal either directly or indirectly through the sensor-conditioning modules.

The data-acquisition tasks are the scanning of the channels and their A/D conversion. A scanner is simply a switch arrangement that allows many analogue input channels to be served by one A/D converter. Software can control these switches to select any one channel for processing at a given time. The A/D converter transforms the original analogue information into computer readable data (digital, binary code). The A/D resolution is specified in terms of bits. An A/D resolution of 12 bits corresponds to approximately 0.025%, 14 bits to 0.006%, and 16 bit to 0.001 5% of the A/D full range or scale.

Parallel digital input/output: The total number of individual channels is mostly grouped in blocks of 8 out of 16 bits with extension possibilities. They are used for individual bit or status sensing or for input of sensors with parallel digital output (for example, wind vanes with Gray code output).

Pulses and frequencies: The number of channels is generally limited to two or four. Typical sensors are wind speed sensors and (tipping-bucket) raingauges. Use is made of low- and high-speed counters accumulating the pulses in CPU memories. A system that registers pulses or the on-off status of a transducer is known as an event recorder.

Serial digital ports: These are individual asynchronous serial input/output channels for data communication with intelligent sensors. The ports provide conventional inter-device communications over short (RS232, several metres) to long (RS422/485, several kilometres) distances. Different sensors or measuring systems can be on the same line and input port, and each of the sensors is addressed sequentially by means of coded words.

1.2.2.2 ***Data processing***

The data-processing hardware is the heart of the CPU and its main functions are to act as the master control of the input/output of data to, and from, the CPU and to carry out the proper processing of all incoming data by means of the relevant software.

The hardware is operated by a microprocessor. Microprocessors do not change the principles of meteorological measurements or observing practices but they do allow the instrument designer to perform technical functions in a new way to make measurements easier, faster and more reliable, and to provide the instrument with higher capabilities, especially in data handling. The adoption of microprocessors considerably reduces hardware costs for some applications. It must be noted, however, that the expanded expectations which may be met by this device will lead very often to a fast-growing and considerably underestimated cost of the development of software.

Existing AWOSs are equipped with 8-bit microprocessors and limited memory (32 to 64 kbytes). New systems using 16- or 32-bit microprocessors surrounded by a considerable amount of solid-state memory (up to 1 Mbyte) are becoming standard. These AWOSs provide more input/output facilities which operate at much higher processing speeds and are capable of performing complex computations. Together with new hardware, sophisticated software is applied which was, some years ago, available only in minicomputer systems. The unit can be equipped with different types of memories such as random access memories (RAM) for data and program storage, non-volatile programmable read-only memories (PROMs) for program storage (programs are entered by means of a PROM programmer), and non-volatile electrically erasable PROMs (EEPROMs) mostly used for the storage of constants which can be modified directly by software. At most stations, the RAM memory is equipped with a battery backup to avoid loss of data during power failures. At non-real-time stations without data transmission facilities, data can be stored in external memories. Mechanical devices with tapes which were used for this purpose for many years are now replaced by memory cards (RAM with battery backup, EEPROMs, etc.), which have a much higher reliability.

1.2.2.3 ***Data transmission***

The data transmission part of the CPU forms the link with the "outside world", which may be the local observer or the maintenance personnel, the central network processing system of the National Meteorological and Hydrological Service, or even directly the users of meteorological information. The equipment is interfaced to the CPU by using commonly available serial and parallel input/output ports. The most suitable means of data transmission depends mainly on the site in question and the readily available transmission equipment. No single solution can be regarded as universally superior, and sometimes the transmission chain requires the use of several means (see section 1.3.2.10).

1.2.3 **Peripheral equipment**

Power supply: The design and capability of an AWS depend critically upon the method used to power it. The most important characteristics of an AWS power supply are high stability and interference-free operation. For safety reasons, and because of the widespread use and common availability of 12 V batteries in motor vehicles, consideration should be given to the use of 12 V direct current power. Where mains power is available, the 12 V batteries could be float-charged from the main supply. Such a system provides the advantage of automatic backup power in the event of a mains power failure. Automatic weather stations deployed at remote sites where no mains power is available must rely upon batteries that may, or may not, be charged by an auxiliary power source, such as a diesel generator, wind- or water-driven generator, or solar cells. However, such low-power systems cannot, in general, support the more complex sensors required for cloud height and visibility measurements, which require large amounts of power. Furthermore, AWSs with auxiliary equipment such as heaters (anemometers, raingauges) and aspirators can also consume considerable power, thus restricting the installation of an AWS to locations where mains power is available. If, because of the need for a versatile and comprehensive system, only the mains can supply sufficient power for full operation, provision should be made for support, from a backup supply, of at least the system clock, the processor and any volatile memory that may contain recent data needed to restart the station automatically.

Real-time clock: An essential part of data processing is a 24 h real-time clock powered by a battery, which ensures that the time is kept even during power outages. Ensuring the accuracy of actual AWS clocks requires special attention to guarantee correct read-outs, sample intervals and time stamps. At some AWSs, devices are used to synchronize the clock with broadcast radio time reference signals or the Global Positioning System.

Built-in test equipment: Vital parts of an AWS often include components whose faulty operation or failure would seriously degrade or render useless the principal output. The inclusion of circuits to monitor automatically these components' status is an effective means of continuously controlling their performance during operation. Examples are: a power-failure detector which restarts the processor and continues the AWS function after a power failure; a "watchdog" timer to monitor the proper operation of microprocessors; and test circuits for monitoring the operation of station subsystems such as battery voltage and charger operation, aspirators (temperature and humidity screens), A/D converters, heaters, etc. Status information can be automatically displayed on site or input into the CPU for quality-control and maintenance purposes.

Local display and terminals: Operational requirements often require observations to be entered or edited manually, for example at semi-automatic weather stations. Depending on the requirements, and on the station designer, different types of local terminals are used for this purpose, including a simple numerical light-emitting diode (LED) display with keyboard forming an integral part of the CPU, a screen with keyboard, or even a small personal computer installed at some distant indoor location. For maintenance purposes, special handheld terminals are sometimes used which can be plugged directly into the station. For particular applications, such as AWSs at airports or simple aid-to-the-observer stations, digital displays are connected for the visualization of data at one or more places at the site. On request, a printer or graphical recorders can be added to the station.

1.3 AUTOMATIC WEATHER STATION SOFTWARE

When designing or specifying an AWS it is a guiding principle that the cost of developing and testing the software will be one of the largest financial elements in the package. Unless great care is exercised in the preliminary design and strong discipline maintained while coding, complex software readily become inflexible and difficult to maintain. Minor changes to the requirements — such as those often induced by the need for a new sensor, code changes, or changes in quality-control criteria — may often result in major and very expensive software revisions.

In general, a distinction can be made between application software consisting of algorithms for the proper processing of data in accordance with user specifications, and system software inherently related to the microprocessor configuration and comprising all software to develop and run application programs.

Advice on the development of algorithms for AWSs is given in section 1.1.3 above. Discussion of the design of algorithms for synoptic AWSs is found in WMO (1987), and for the processing of surface wind data in WMO (1991). Information on the algorithms used by Members can be found in WMO (2003). For detailed information on sampling, data reduction and quality management, the appropriate chapters in Part IV should be consulted.

1.3.1 **System software**

The software for many existing AWSs is developed by the manufacturer in accordance with user requirements and is put into the CPU memory in a non-readable format for the user (so-called firmware), thus turning the CPU into a sort of black box. The user can execute only predetermined commands and, as a consequence, depends entirely on the manufacturer in the event of malfunctions or modifications.

Fortunately, the increasing demand for data-acquisition systems for industrial process control has opened up new possibilities. Users can now develop their own application software (or leave it to a software company or even the manufacturer of the station) using programming languages like Basic, Pascal or, in particular, C, and using readily available utility packages for data acquisition, statistics, storage and transmission. The result is that the user acquires more insight into, and control over, the different processes and becomes consequently less dependent on the manufacturer of the station.

In recent systems, increasing use is made of well-proven real-time multitasking/multi-user operating systems, which were available only for minicomputers in the past. They are *real-time* because all operations are activated by hardware and software interrupts, *multitasking* because different tasks can be executed quasi-simultaneously following a predetermined priority, and *multi-user* because different users can have quasi-simultaneous access to the system. Software developers can give their full attention to the development of application programs in the language of their choice while leaving the very difficult and complex control and execution of tasks to the operating system.

1.3.2 **Application software**

The processing functions that must be carried out either by the CPU, the sensor interfaces, or a combination of both, depend to some extent on the type of AWS and on the purpose for which it is employed. Typically, however, some or all of the following operations are required: initialization, sampling of sensor output, conversion of sensor output to meteorological data, linearization, averaging, manual entry of observations, quality control, data reduction, message formatting and checking and data storage, transmission and display. The order in which these functions are arranged is only approximately sequential. Quality-control may be performed at different levels: immediately after sampling, after deriving meteorological variables, or after the manual entry of data and message formatting. If there are no checks on data quality-control and message content, the AWS data are likely to contain undetected errors. While linearization may be inherent in the sensor or signal-conditioning module, it should always be carried out before the calculation of an average value.

The execution of the application software is governed by a schedule that controls when specific tasks must be executed. The overview of AWS application software in the following paragraphs is limited to some practical aspects related to AWSs.

1.3.2.1 ***Initialization***

Initialization is the process that prepares all memories, sets all operational parameters and starts running the application software. In order to be able to start normal operations, the software first requires a number of specific parameters, such as, among others, those related to the station (station code number, altitude, latitude and longitude); date and time; physical location of the sensor in the data-acquisition section; type and characteristics of sensor-conditioning modules;

conversion and linearization constants for sensor output conversion into meteorological values; absolute and rate of change limits for quality-control purposes; and data buffering file location. Depending on the station, all or part of these parameters may be locally input or modified by the user through interactive menus on a terminal. In the latest generation of AWSs, initialization may be executed remotely, for instance, by the central network processing system or by a remote personal computer. In addition to full initialization, a partial initialization should be programmed. This automatically restores normal operation, without any loss of stored data, after a temporary interruption caused by real-time clock setting, maintenance, calibration or power failure.

1.3.2.2 ***Sampling and filtering***

Sampling can be defined as the process of obtaining a well-spaced sequence of measurements of a variable. To digitally process meteorological sensor signals, the question arises of how often the sensor outputs should be sampled. It is important to ensure that the sequence of samples adequately represents significant changes in the atmospheric variable being measured. A generally accepted rule of thumb is to sample at least once during the time constant of the sensor. However, as some meteorological variables have high frequency components, proper filtering or smoothing should be accomplished first by selecting sensors with a suitable time-constant or by filtering and smoothing techniques in the signal-conditioning modules (see Part IV, Chapter 2).

Considering the need for the interchangeability of sensors and homogeneity of observed data, it is recommended:[12]

(a) That samples taken to compute averages should be obtained at equally spaced time intervals which:

    (i) Do not exceed the time constant of the sensor; or

    (ii) Do not exceed the time constant of an analogue low-pass filter following the linearized output of a fast response sensor; or

    (iii) Are sufficient in number to ensure that the uncertainty of the average of the samples is reduced to an acceptable level, for example, smaller than the required accuracy of the average;

(b) That samples to be used in estimating extremes of fluctuations should be taken at least four times as often as specified in (i) or (ii) above.

1.3.2.3 ***Raw-data conversion***

The conversion of raw sensor data consists of the transformation of the electrical output values of sensors or signal-conditioning modules into meteorological units. The process involves the application of conversion algorithms making use of constants and relations obtained during calibration procedures.

An important consideration is that some sensors are inherently non-linear, namely their outputs are not directly proportional to the measured atmospheric variables (for example, a resistance thermometer), that some measurements are influenced by external variables in a non-linear relation (for example, some pressure and humidity sensors are influenced by the temperature) and that, although the sensor itself may be linear or incorporate linearization circuits, the variables measured are not linearly related to the atmospheric variable of interest (for example, the output of a rotating beam ceilometer with photo detector and shaft-angle encoder providing backscattered light intensity as a function of angle is nonlinear in cloud height). As a

---

[12] Recommended by the Commission for Instruments and Methods of Observation at its tenth session (1989) through Recommendation 3 (CIMO-X).

consequence, it is necessary to include corrections for non-linearity in the conversion algorithms as far as this is not already done by signal-conditioning modules. Linearization is of particular importance when mean values must be calculated over a certain time. Indeed, when the sensor signal is not constant throughout the averaging period, the "average then linearize" sequence of operations can produce different results from the "linearize then average" sequence. The correct procedure is to only average linear variables.

1.3.2.4 ***Instantaneous meteorological values***

The natural small-scale variability of the atmosphere, the introduction of noise into the measurement process by electronic devices and, in particular, the use of sensors with short time-constants make averaging a most desirable process for reducing the uncertainty of reported data.

In order to standardize averaging algorithms it is recommended:[13]

(a) That atmospheric pressure, air temperature, air humidity, sea-surface temperature, visibility, among others, be reported as 1 to 10 min averages, which are obtained after linearization of the sensor output;

(b) That wind, except wind gusts, be reported as 2 or 10 min averages, which are obtained after linearization of the sensor output.

These averaged values are to be considered as the "instantaneous" values of meteorological variables for use in most operational applications and should not be confused with the raw instantaneous sensor samples or the mean values over longer periods of time required from some applications. One-minute averages, as far as applicable, are suggested for most variables as suitable instantaneous values. Exceptions are wind (see (b) above) and wave measurements (10 or 20 min averages). Considering the discrepancy of observations between the peak gust data obtained from wind measuring systems with different time responses, it is recommended that the filtering characteristics of a wind measuring chain should be such that the reported peak gust should represent a 3 s average. The highest 3 s average should be reported. In practice, this entails sampling the sensor output and calculating the 3 s running mean at least one to four times a second.

Some specific quantities for which data conversion is necessary and averaging is required before conversion are given in Part IV, Chapter 2.

1.3.2.5 ***Manual entry of observations***

For some applications, interactive terminal routines have to be developed to allow an observer to enter and edit visual or subjective observations for which no automatic sensors are provided at the station. These typically include present and past weather, state of the ground and other special phenomena.

1.3.2.6 ***Data reduction***

Beside instantaneous meteorological data, directly obtained from the sampled data after appropriate conversion, other operational meteorological variables are to be derived and statistical quantities calculated. Most of them are based on stored instantaneous values, while, for others, data are obtained at a higher sampling rate, as for instance is the case for wind gust computations. Examples of data reduction are the calculation of dewpoint temperature values from the original relative humidity and air temperature measurements and the reduction of pressure to mean sea level. Statistical data include data extremes over one or more time periods

---

[13] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 6 (CIMO-IX).

(for example, temperature), total amounts (for example, rain) over specific periods of time (from minutes to days), means over different time periods (climatological data), and integrated values (radiation). These variables or quantities can be computed at an AWS or at a central network processing system where more processing power is normally available.

CIMO is involved in an extensive programme to survey and standardize algorithms for all variables. The results are published in the WMO (2003).

Formal recommendations exist for the computation of pressure tendency[14] and humidity quantities[15] (Part I, Chapter 4, Annex 4.B).

WMO investigated the methods for pressure reduction used by Members in 1952 (WMO, 1954) and concluded that the "international formula" (using the formula of Laplace or Angot's tables) or some "simplified" methods are in practice (for example, for "low-level" stations[16], see, Part I, Chapter 3). As a result of this inquiry, a study of the standardization of methods of reduction was undertaken and one general equation of pressure reduction was recommended as standard[17] (WMO, 1964). Nevertheless, this recommended method, the "international formula" and methods using simplified formulae are still in common practice (WMO, 1968).

1.3.2.7 ***Message coding***

Functional requirements often stipulate the coding of meteorological messages in accordance with WMO (2011*b*). Depending on the type of message and the elements to be coded, the messages can be generated fully or semi-automatically. Generating fully automatic messages implies that all elements to be coded are measurable data, while generating semi-automatic messages involves the intervention of an observer for entering visual or objective observations, such as present and past weather, the state of the ground, and cloud type. Message coding algorithms should not be underestimated and require considerable efforts not only for their development but also for updating when formats are altered by international, regional and national regulations. They also occupy a considerable amount of memory that can be critical for small performance stations. It should be noted that observational data could be transmitted to the central network processing system, where more computer power is normally available for message coding.

1.3.2.8 ***Quality control***

The purpose of quality-control at an AWS is to minimize automatically the number of inaccurate observations and the number of missing observations by using appropriate hardware and software routines. Both purposes are served by ensuring that each observation is computed from a reasonably large number of quality-controlled data samples. In this way, samples with large spurious errors can be isolated and excluded and the computation can still proceed, uncontaminated by that sample.

Quality-control achieves assured quality and consistency of data output. It is achieved through a carefully designed set of procedures focused on good maintenance practices, repair, calibration, and data quality checks. Currently, there is no agreed set of procedures or standards for the various AWS platforms. Such a set of procedures should be developed and documented.

In modern AWSs, the results of data quality-control procedures for sensors which reveal the reasons why a measurement is suspect or erroneous, and the results of hardware self-checks

---

[14] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 7 (CIMO-IX).

[15] Recommended by the Commission for Instruments and Methods of Observation at its tenth session (1989) through Recommendation 7 (CIMO-X).

[16] Recommended by the Commission for Instruments and Methods of Observation at its first session (1953) through Recommendation 13 (CIMO-I) and adopted by EC-IV.

[17] Based on the recommendations by the CIMO-I Working Committee II on "Reduction of Pressure" (WMO, 1954, Part 2).

by built-in test equipment, are stored in appropriate housekeeping buffers. The visual display of these status indicators forms a very handy tool during field maintenance. The transmission of housekeeping buffers – either as an appendix to the routine observational message, or as a clocked or on-request housekeeping message, from a network of AWSs to a central network processing system – is a valuable possible approach to the maintenance of meteorological equipment.

Real-time procedures for the quality-control of AWS data are highly advisable, and detailed recommendations exist in Part IV, Chapter 1, and as basic quality-control procedures in WMO (1993). The following is a practical elaboration of the recommendations.

Intra-sensor checks

Intra-sensor checks: This is when each sensor sample is checked at the earliest practical point in the processing, taking into account sensor and signal-conditioning response functions, for a plausible value and a plausible rate of change.

Plausible value: This is a gross check that the measured value lies within the absolute limits of variability. These limits are related to the nature of the meteorological variable or phenomena but depend also on the measuring range of selected sensors and data-acquisition hardware. Additional checks against limits which are functions of geographical area, season and time of year could be applied. Suggested limits for these additional checks are presented in Tables 6.3–6.9 in Chapter 6 of WMO (1993). The checks provide information as to whether the values are erroneous or suspect.

Plausible rate of change: This checks for a plausible rate of change from a preceding acceptable level. The effectiveness of the check depends upon the temporal consistency or persistence of the data and is best applied to data of high temporal resolution (high sampling rate) as the correlation between adjacent samples increases with the sampling rate. One obvious difficulty is determining how quickly an atmospheric variable can change taking into account the response characteristics of the sensor in question. Additional time consistency checks using comparisons of data between two consecutive reports can be made. WMO (1993) provides checking tolerances for different time periods on the synoptic scales (1, 2, 3, 6, 12 h) for air temperature, dewpoint, and pressure tendency.

Inter-sensor checks

It is possible to make internal consistency checks of a variable against other variables, based upon established physical and meteorological principles. Some examples are as follows: dewpoint cannot exceed ambient temperature; precipitation without clouds overhead or just after they have passed overhead is very unlikely; non-zero wind-speed and zero wind-direction variance strongly suggest a wind-direction sensor problem; and zero average wind speed and non-zero wind direction (variance) suggest a defective wind-speed sensor.

Observations entered manually

When a manually observed quantity is entered into the AWS, the inter- and intra-sensor checks mentioned above can be conducted. Some special consistency checks are suggested in WMO (1993) concerning present weather with visibility; present weather with cloud cover; cloud cover, weather and cloud information; present weather with air temperature; present weather with dewpoint temperature; height of clouds with types of clouds; and state of the sea with wind speed.

Hardware checks

During operation, the performance of an AWS deteriorates with the ageing of hardware components, exposure to untested situations, improper maintenance, product failure, and so on. Therefore, it is important to implement and execute automatically and periodically internal self-check features using built-in test equipment for AWS hardware and to make the results of these tests available to appropriate personnel or to store the results in housekeeping buffers. These buffers can be examined, and the information contained in them should be used to classify the measurements as correct, erroneous or suspect.

Message checking

For AWSs equipped with software for coding messages and for transmitting the messages over the Global Telecommunication System, it is of vital importance that all the above checks are executed very carefully. In addition, compliance with regulations concerning character, number, format, and so forth, should be controlled. Proper actions are to be considered in cases of values that are classified as suspect.

1.3.2.9 ***Data storage***

Processed and manually observed data, including quality-control status information (housekeeping data) must be buffered or stored for some time in the AWS. This involves a relevant database that must be updated in real time. The number of database cells and memory required is determined as a function of the maximum possible number of sensors, intermediate data, derived quantities and the required autonomy of the station. In general, a circular memory structure is adopted allowing the old data to be overwritten by new incoming data after a predetermined time. The database structure should allow easy and selective access by means of data transfer and transmission algorithms.

Depending on observational requirements and the type of station, the data can be transferred at regular time intervals from the AWS main memory to other kinds of storage devices, such as a removable memory.

1.3.2.10 ***Data transmission***

Dictated by operational requirements and data transmission facilities, data transmission between an AWS and either local users or the central network processing system can operate in different modes, as follows:

(a) In response to external commands, as this is the most common basic mode given that it allows more control of the station, such as initialization, setting and resetting of the real-time clock, inhibiting faulty sensors, selective database transfer, and so on. Upon reception and after transmission control of an external command, a task schedule activates the appropriate task or subroutine as requested by the command;

(b) At periodic time intervals controlled by the AWS time scheduler;

(c) In AWS emergency conditions when certain meteorological thresholds are crossed.

In general, readily available data transmission software packages can be used for proper data transfer and control and for transmission protocols. As data transmission means are subject to several interference sources, careful attention must be paid to adequate error coding, such as parity bits and cyclical redundancy codes. A brief review of some telecommunications options for establishing an AWS network follows.

One-way communications

A simple AWS network could use one-way communications where the remote stations operate on a timed cycle to scan the sensor channels, or otherwise when alarm conditions are triggered, to dial up over telephone lines the central control and data-acquisition computer, and having established the link, deliver their data messages. Each AWS might have a serial interface to an analogue modem, and data transmission would be at a rate, of say, 9 600 bits per second (bps) using audio tones. The advantage of this point-to-point communications system is that it uses well-established, simple technology and ordinary voice-grade telephone lines. The cost, which should be modest, depends on a tariff formula including distance and connection time. The drawbacks are that data security is only moderate; data volumes must be relatively low; no powerful network architectures can be used; and telecommunications companies may restrict future access to analogue data circuits as the technology moves inexorably to broadband digital networks.

Two-way communications

A more powerful network has two-way communications so that the central computer may poll the network stations, not only at the synoptic times, or hourly, but on a random access basis when a forecaster or hydrologist wishes to obtain a current update on weather conditions at a particular site or sites. The remote stations would initiate the procedure for sending their own alarm messages in real time. Two-way communication also enables the remote station to send command messages to change its mode of operation, or to have new operating software downloaded onto its processor.

AWS network communication

The network might use landline or radio communications (especially for very remote sites) or a combination of both. The advantage of using a telecommunications service provider is that all responsibility for maintenance of the network service and probably the communications interfaces lies with the provider, who should respond promptly to the AWS system manager's fault reports. Note the need to be able to determine on which side of the communications interface (AWS or telecommunications circuits) the fault lies, which may be problematical. AWS networks have often used dial-up circuits in the Public Switched Telephone Network (PSTN), with costs related to distance and connect time, depending on the tariffs of the local communications provider. The other option is to have a "private network" network based on dedicated leased lines of defined quality. There is no switching delay in establishing the circuits, higher transmission speeds are available, and there is a high certainty that the circuit will be maintained. The leasing costs depend on the line distances, but not on the volume of data. Costs are higher than for dial-up connections when the volume of data is fairly low.

Integrated services digital network

Many telecommunications authorities offer an integrated services digital network that provides for voice, data and video transmission with pulse-code modulation over upgraded PSTN cables and switches. A basic channel provides for 64 kbps data, which may carry X.25 packet-switch or frame-relay protocols. The digital circuits provide very high data security.

Wide area network communications

With the worldwide increase in data traffic and the use of modern communications protocols, together with the increased computing and data-storage capability at remote terminals, it is now common to view the remote AWS and the central control and data-acquisition computer as nodes of a wide area network (WAN). The data or control message is divided into "packets" according to rules (protocols) such as X.25 or the faster frame relay. Each data packet is routed through the telecommunication provider's switched data network and may arrive at the destination by different routes (making efficient use of the network with other unrelated packets). At the destination, the packets are reassembled under the protocol after variable delays to reform the message. Error detection with the automatic resending of corrupted or lost packets ensures reliable transmission. Note the contrast with ordinary PSTN based on circuit-switching technology, in which a dedicated line is allocated for transmission between two parties. Circuit-switching is ideal when real-time data (like live audio and video) must be transmitted quickly and arrive in the same order in which it was sent. Packet switching is more efficient and robust for data that can withstand some short delay in transmission. Message costs are related to connect time and data volume. There should be a means to terminate the connection reliably when data collection is finished, as a faulty AWS may keep the line open and incur unwanted costs.

Frame relay and asynchronous transfer mode

Frame relay is a packet-switching, networking protocol for connecting devices on a WAN, operating at data speeds from 64 kbps to 2 Mbps or higher, depending on line quality. Unlike a point-to-point private line, network switching occurs between the AWS and the central station. In fact, there is a private line to a node on the frame relay network, and the remote location has a private line to a nearby frame relay node. The user gets a "virtual private network". Costs are decreasing and are independent of the volume of data or the spent time connected. However, frame relay is being replaced in some areas by newer, faster technologies, such as asynchronous transfer mode (ATM). The ATM protocol attempts to combine the best of both worlds – the guaranteed delivery of circuit-switched networks and the robustness and efficiency of packet-switching networks.

Transmission protocol

A de facto standard for transmission between computers over networks is the Transmission Control Protocol/Internet Protocol (TCP/IP). The Internet Protocol (IP) specifies the format of packets, called "datagrams" and the addressing scheme. The higher-level protocol TCP establishes a virtual connection between source and destination so that two-way data streams may be passed for a time and so that datagrams are delivered in the correct sequence with error correction by retransmission. The TCP also handles the movement of data between software applications. The functioning of the Internet is based on TCP/IP protocols, and the IP is also used in WANs, where the nodes have processing capability and high volumes of data are exchanged over the network. The IP enables the AWS data and road condition analyses performed in the central station computer to be shared by national and regional road administrations over a private Intranet.

Switched or dedicated circuits

It is necessary to decide whether to use cheaper switched data circuits where telecommunications network access has to be shared with other users, or to lease much more expensive dedicated circuits that provide reliable, high-speed, real-time communications. The switched network will have some latency where there will be a delay of as much as a few seconds in establishing the circuit, but packet-switch protocols handle this without difficulty. The reliability consideration, the amount of data to be exchanged with each message or special "downloads" to the remote stations, as well as the operational need for actual real-time communications, will help determine the choice. The seasonal factor will also have a bearing on the choice of communications. If the critical use of the road meteorological data is only for a few months of the year, maintaining a year-round dedicated communications network imposes a high overhead cost per message. Actual message costs will depend on the charging formulas of the telecommunications company, and will include factors like data rate, distance of link, connection time and whether the terminal modems are provided by the company. The local telecommunications companies will be ready to offer guidance on the choice of their services.

1.3.2.11 ***Maintenance and calibration***

Specific software routines are incorporated in the application software allowing field maintenance and calibration. Such activities generally involve running interactive programs for testing a particular sensor, AWS reconfiguration after the replacement of sensors or models, resetting of system parameters, telecommunication tests, entering new calibration constants, and so on. In general, maintenance and calibration is conducted in an off-line mode of operation, temporarily interrupting the normal station operation.

1.3.2.12 ***Data display***

In addition to data display routines for the different functions mentioned in the above paragraphs, operational requirements often specify that selected data should be displayed locally with periodic updating in real time or, on LED displays, existing terminals, or on special screens. Examples of this are AWSs at airports and at environmental control sites. In some countries, a printout of local data or a graphical display on pen recorders is required.

1.4 AUTOMATIC WEATHER STATION SITING CONSIDERATIONS

The siting of an AWS is a very difficult matter and much research remains to be done in this area. The general principle is that a station should provide measurements that are, and remain, representative of the surrounding area, the size of which depends on the meteorological application. Existing guidelines for conventional stations are also valid for AWSs and are given in Part I as well as in WMO (2010*a*, 2010*b*, 2014).

Some AWSs have to operate unattended for long periods at sites with difficult access both on land and at sea. Construction costs can be high and extra costs can be necessary for servicing. They may have to operate from highly unreliable power supplies or from sites at which no permanent power supply is available. The availability of telecommunication facilities should be considered. Security measures (against lightning, flooding, theft, vandalism, and so forth) are to be taken into account and the stations must, of course, be able to withstand severe meteorological conditions. The cost of providing systems capable of operating under all foreseen circumstances at an automatic station is prohibitive; it is essential that, before specifying or designing an AWS, a thorough understanding of the working environment anticipated for the AWS be obtained. At an early stage of planning, there should be a detailed analysis of the relative importance of the meteorological and technical requirements so that sites can be chosen and approved as suitable before significant installation investment is made.

1.5 CENTRAL NETWORK DATA PROCESSING

An AWS usually forms part of a network of meteorological stations and transmits its processed data or messages to a central network processing system by various data telecommunication means. The specification of the functional and, consequently, the technical requirements of a central system is a complex and often underestimated task. It requires good cooperation between AWS designers, specialists in telecommunication, software specialists, and data users. Decisions have to be taken concerning the tasks that must be executed in the central system and at the AWSs. In fact, depending on the application, certain functions at an AWS could be transferred to the central system where more computer power and memory are available. Examples are long mathematical calculations, such as the reduction of atmospheric pressure and coding of meteorological messages. The AWS data buffers can be reduced to an operational minimum when they are regularly transferred to the central system. It is good practice to first arrange for an agreement on the functional requirements of both the central system and the AWS before specifying their technical requirements.

1.5.1 Composition

The composition of a central network processing system depends considerably not only on the functions to be accomplished, but also on local facilities. Use can be made of powerful personal computers or workstations, operating in a real-time multitasking and multi-user environment. However, existing telecommunication and processing systems are used. Central network processing systems are increasingly integrated into a local area network allowing distribution and execution of tasks at the most convenient place by the most appropriate people.

The main functions of a central network system are data acquisition, including decoding of messages from the AWS network, remote control and housekeeping of AWSs, network monitoring and data quality control, further processing of data to satisfy user requirements, access to the network database, data display, and data transfer to internal or external users. The latter may include the Global Telecommunication System if the data are exchanged internationally.

1.5.2 Quality management of network data

This topic is discussed further in Part IV, Chapter 1. It is recommended that operators of networks:[18]

(a) Establish and test near-real-time measurement monitoring systems in which reported values are regularly tested against analysed fields corresponding to the same measurement location;

(b) Establish effective liaison procedures between the monitoring service and the appropriate maintenance and calibration services to facilitate rapid response to fault or failure reports from the monitoring system.

Automated quality-control procedures at an AWS have their limitations and some errors can go undetected even with the most sophisticated controls, such as long-term drifts in sensors and modules. Data transmission from an AWS adds another source of error. Therefore, it is recommended that additional quality-control procedures should be executed by a network monitoring system forming part of the central network system. Quality-control procedures of prime importance in such a monitoring system include:

(a) Detecting data transmission errors; the required routines depend on the transmission protocol and cyclic redundancy codes used;

(b) Checking the format and content of WMO coded messages (WMO, 1993);

(c) Further processing of data to exclude or otherwise deal with data flagged as erroneous or suspect in the AWS housekeeping files.

Interactive display systems also allow complementary quality-control of incoming data. Time series for one or more variables and for one or more stations can be displayed on colour screens; statistical analysis can be used by trained and experienced personnel to detect short- and long-term anomalies that are not always detected by fully automatic quality-control algorithms.

Monitoring algorithms, by which reported values are regularly tested in space and time against an analysed numerical field, are very powerful ways to identify errors and to establish the need for investigative or remedial action. The low level of turbulent fluctuations in atmospheric pressure and the confidence with which local geographic influences can be removed by normalizing all observations to a common reference level make atmospheric pressure a prime candidate for this type of quality control. By averaging over space or time, observations with other variables should be susceptible to this analysis as well. However, local orographic effects must be carefully considered and taken into account.

1.6 MAINTENANCE

The cost of servicing a network of automatic stations on land and, in particular, at sea can greatly exceed the cost of their purchase. It is, therefore, of central importance that AWSs are designed to have the greatest possible reliability and maintainability. Special protection against environmental factors is often justified, even when initial costs are high.

---

[18] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 5 (CIMO-IX).

It is evident that any complex system requires maintenance support. Corrective maintenance is required for component failures. Hardware components may fail for many reasons; computer programs can also fail because of errors in design that can go undetected for a long time. To minimize corrective maintenance and to increase the performance of an AWS, well-organized preventive maintenance is recommended. Preventive maintenance is required for all system components, not only cleaning and lubricating the mechanical parts. In view of the increasing reliability of the electronic components of an AWS, preventive maintenance, including services and sensor calibration, will become the controlling factor in maintenance.

Adaptive maintenance is required to take into account the rapid changes in technology and the availability of spare parts after a few years. Indeed, costs for repair and components often increase quite rapidly after a system is no longer in active distribution, making it necessary to replace modules by new ones with different technology, as exact replacements are seldom found. Examples include transferring data from one recording medium to another and programs and operating systems from one processor to another, introducing modular changes for system reliability, connecting with new telecommunication systems, and so on. In order to reduce the costs for this kind of maintenance, it is desirable that widely accepted standards on equipment and interfaces, as well as on software, be established and included in AWS technical specifications.

Since the maintenance of a network of automatic stations is often a grossly underestimated task, it is essential to organize maintenance according to a rational plan that details all the functions and arranges them so as to minimize costs without adversely affecting performance. The modular structure of many modern automatic stations allows maintenance to take place in the field, or at regional and national centres.

Field maintenance: In general, it is not advisable to repair AWS sensors or other modules in the field because conditions do not favour effective work. Also, because of high staff costs and relatively low equipment costs, it is more cost-effective to discard faulty modules rather than to repair them. It is recommended that corrective maintenance in the field be carried out by specialized technical personnel from a regional or national centre, depending on the size of the country, and to leave simple preventive maintenance to the local observer (when available). The periodic transmission of self-checking diagnostic information by the AWS is a very desirable practice to ensure rapid response to failures.

Regional centre: At a regional centre, technical personnel should be available to replace or repair modules and sensors which require the detection and elimination of simple defects. The personnel should have good knowledge of the station hardware operation and must be trained in the execution of software maintenance routines. Such regional centres should be equipped with appropriate test equipment and sufficient spare modules and sensors to support the maintenance of the stations in their area. These centres need adequate transportation facilities for conducting field work. Care should be taken to plan and visit periodically the remote sites to check for operational problems, vandalism, site conditions, changes, and so forth. Procedures for emergency visits to the different stations must be established, based on priorities defined at the station.

National centre: A national centre requires more skilled technical personnel, who should be capable of detecting and eliminating complex problems in sensors, modules and data transmission means. The equipment necessary for checking and correcting all parts of an AWS should be available and the work should be performed in the centre. Any recurring defects should be referred to designers or suppliers in charge of correcting the design fault.

As software plays a very important role in each AWS and in the central network processing system, personnel with a profound knowledge of the AWS and central network system software are required. The necessary software development and test facilities should be available. Moreover, the national centre should be able to execute all tasks associated with adaptive maintenance.

With reference to the quality-control of network data, it is desirable to establish effective liaison procedures between the monitoring service and the appropriate maintenance and calibration service in order to facilitate rapid response to fault or failure reports from the monitoring system.

The scheme outlined above is suitable for big countries. For small countries, the tasks of the regional centres could be taken over by the national centre. Developing countries could consider establishing joint maintenance arrangements with neighbouring counties. A common international maintenance centre could be envisaged in order to keep maintenance costs reasonably low. However, such international cooperation would probably require the use of similar equipment. If the Meteorological Service is unable to expand its staff or facilities, contractor services could be used to perform many of the support functions. Such support could, for example, be negotiated as part of the system procurement. However, a maintenance contract should be extremely well prepared and the execution of the contract should be very carefully verified by the appropriate staff.

Suggestions for quality-management techniques are given in Part IV, Chapter 1.

1.7 CALIBRATION

Sensors, in particular AWS sensors with electrical outputs, show accuracy drifts in time and, consequently, need regular inspection and calibration. In principle, the calibration interval is determined by the drift specifications given by the manufacturer and the required accuracy. WMO international instrument intercomparisons also provide some objective indications of sensor accuracy drifts and desirable calibration intervals. As signal conditioning modules and data-acquisition and transmission equipment also form a part of the measuring chain, their stability and correct operation also have to be controlled or calibrated periodically. The summary given below is limited to practical aspects related to AWSs. Refer to the different chapters of Part I and to Part IV, Chapter 4, for more detailed information on calibration techniques and methods.

Initial calibration: It is easy to overlook the requirement that appropriate calibration facilities and instrumentation should be available prior to the procurement and installation of AWSs in order to be able to verify the specifications given by the manufacturer, to test the overall performance of the station and to verify that transportation did not affect the measuring characteristics of the equipment.

Field inspection: The periodic comparison of AWS sensors with travelling standards at the station is an absolute requirement to monitor the performance of the sensors. Travelling standards having similar filtering characteristics to the AWS measuring chain and with a digital read-out are to be preferred. In many countries, two travelling standards of the same type are used to prevent possible accuracy change problems due to transportation. In order to be able to detect small drifts, the travelling standards should have an accuracy that is much better than the relevant station sensor and should be installed during the comparison process in the same environmental conditions as the sensors for a sufficiently long time. As signal conditioning modules and data-acquisition equipment, such as the A/D converter, can also show performance drifts, appropriate electrical reference sources and multimeters should be used to locate anomalies.

Before and after field inspections, the travelling standards and reference sources must be compared with the working standards of the calibration laboratory. The maintenance service must be informed as soon as possible when accuracy deviations are detected.

Laboratory calibration: Instruments at the end of their calibration interval, instruments showing an accuracy deviation beyond allowed limits during a field inspection and instruments repaired by the maintenance service should return to a calibration laboratory prior to their re-use. Sensors should be calibrated in a conditioned environment (environmental chambers) by means of appropriate working standards. These working standards should be compared and calibrated periodically with secondary standards and be traceable to international standards.

Attention should also be paid to the calibration of the different components forming the measuring and telemetry chain, in particular the signal-conditioning modules. This involves appropriate voltage, current, capacitance and resistance standards, transmission test equipment and high-accuracy digital multimeters. Highly accurate instruments or data-acquisition systems are required for calibration. A computer is desirable for calculation of calibration constants. These constants will accompany the sensor or module between calibrations and must be entered in the AWS whenever a sensor or module is replaced or installed in an AWS during field maintenance.

A schedule should be set up to compare periodically the secondary standards of the calibration laboratory with national, international or regional WMO primary standards.

1.8 TRAINING

As an AWS is based on the application of technology that differs considerably from the equipment at conventional stations and networks, a comprehensive review of existing training programmes and of the skills of the necessary technical staff is obviously required. Any new training programme should be organized according to a plan that is geared to meeting user needs. It should especially cover the maintenance and calibration outlined above and should be adapted to the system. Requesting existing personnel to take on new functions, even if they have many years of experience with conventional stations, is not always possible and may create serious problems if they have no basic knowledge of electrical sensors, digital and microprocessor techniques or computers. It could be necessary to recruit new personnel who have such knowledge. Personnel competent in the different areas covered by automatic stations should be present well before the installation of a network of AWSs (see WMO, 1997).

It is essential that AWS equipment manufacturers provide very comprehensive operational and technical documentation together with operational and technical training courses. Generally, two sets of documentation are required from the manufacturer: user manuals for operational training and use of the system, and technical manuals with more complex documentation describing in great technical detail the operating characteristics of the system, down to sub-unit and even electronic component level and including maintenance and repair instructions. These manuals can be considered as the basic documentation for training programmes offered by the manufacturer and should be such that they can serve as references after the manufacturer's specialists are no longer available for assistance.

For some countries, it may be advisable to organize common training courses at a training centre that serves neighbouring countries. Such a training centre would work best if it is associated with a designated instrument centre and if the countries served have agreed on the use of similar standardized equipment.

REFERENCES AND FURTHER READING

World Meteorological Organization, 1954: *Reduction of Atmospheric Pressure*. Technical Note No. 7 (WMO-No. 36, TP. 12). Geneva.

———, 1964: *Note on the Standardization of Pressure Reduction Methods in the International Network of Synoptic Stations: Report of a Working Group of the Commission for Synoptic Meteorology*. Technical Note No. 61 (WMO-No. 154, TP. 74). Geneva.

———, 1968: *Methods in Use for the Reduction of Atmospheric Pressure*. Technical Note No. 91 (WMO-No. 226, TP. 120). Geneva.

———, 1987: *Some General Considerations and Specific Examples in the Design of Algorithms for Synoptic Automatic Weather Stations* (D.T. Acheson). Instruments and Observing Methods Report No. 19 (WMO/TD-No. 230). Geneva.

———, 1988: *WMO International Ceilometer Intercomparison (United Kingdom, 1986)* (D.W. Jones, M. Ouldridge and D.J. Painting). Instruments and Observing Methods Report No. 32 (WMO/TD-No. 217). Geneva.

———, 1989*a*: *WMO International Hygrometer Intercomparison* (J. Skaar, K. Hegg, T. Moe and K. Smedstud). Instruments and Observing Methods Report No. 38 (WMO/TD-No. 316). Geneva.

———, 1989*b*: Preliminary results of the WMO automatic sunshine duration measurement comparison 1988/89 in Hamburg (K. Dehne). *Papers Presented at the Fourth WMO Technical Conference on Instruments and Methods of Observation (TECIMO-IV).* Instruments and Observing Methods Report No. 35 (WMO/TD-No. 303). Geneva.

———, 1990: *The First WMO Intercomparison of Visibility Measurements: Final Report (United Kingdom 1988/1989)* (D.J. Griggs, D.W. Jones, M. Ouldridge and W.R. Sparks). Instruments and Observing Methods Report No. 41 (WMO/TD-No. 401). Geneva.

———, 1991: *Guidance on the Establishment of Algorithms for Use in Synoptic Automatic Weather Stations: Processing of Surface Wind Data* (D.J. Painting). Instruments and Observing Methods Report No. 47 (WMO/TD-No. 452). Geneva.

———, 1992*a*: *International Meteorological Vocabulary* (WMO-No. 182). Geneva.

———, 1992*b*: *The WMO Automatic Digital Barometer Intercomparison: Final Report* (J.P. van der Meulen). Instruments and Observing Methods Report No. 46 (WMO/TD-No. 474). Geneva.

———, 1993: *Guide on the Global Data-processing System* (WMO-No. 305). Geneva.

———, 1994: WMO solid precipitation measurement intercomparison: Preliminary results (B.E. Goodison, E. Elomaa, V. Golubev, T. Gunther and B. Sevruk). *Papers Presented at the WMO Technical Conference on Instruments and Methods of Observation (TECO-94).* Instruments and Observing Methods Report No. 57 (WMO/TD-No. 588). Geneva.

———, 1997: *Guidance on Automatic Weather Systems and their Implementation*. Instruments and Observing Methods Report No. 65 (WMO/TD-No. 862). Geneva.

———, 2000: Operation of automated surface observing systems in harsh climatological environments (M.D. Gifford, G.M. Pearson and K. Hegg). *Papers Presented at the WMO Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO-2000).* Instruments and Observing Methods Report No. 74 (WMO/TD-No. 1028). Geneva.

———, 2003: *Algorithms Used in Automatic Weather Stations: Evaluation of Questionnaire* (M.D. Gifford). Instruments and Observing Methods Report No. 78 (WMO/TD-No. 1160). Geneva.

———, 2010*a*: *Guide to the Global Observing System* (WMO-No. 488). Geneva.

———, 2010*b*: *Manual on the Global Observing System* (WMO-No. 544), Volume I. Geneva.

———, 2011*a*: *Guide to Climatological Practices* (WMO-No. 100). Geneva.

———, 2011*b*: *Manual on Codes* (WMO-No. 306), Volumes I.1 and I.2. Geneva.

———, 2011*c*: *Technical Regulations* (WMO-No. 49), Volume I. Geneva.

———, 2014: *Guide to Meteorological Observing and Information Distribution Systems for Aviation Weather Services* (WMO-No. 731). Geneva.