SECTION: Table_of_Contents_Chapter
Chapter title in running head: CHAPTER 1. MEASUREMENTS AT AUTOMATIC WE…
Chapter_ID: 8_II_1_en
Part title in running head: PART II. OBSERVING SYSTEMS
SECTION: Chapter_book
Chapter title in running head: CHAPTER 1. MEASUREMENTS AT AUTOMATIC WE…
Chapter_ID: 8_II_1_en
Part title in running head: PART II. OBSERVING SYSTEMS

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).

An AWS is now a common set of equipment found as part of a surface meteorological observing station. The majority of the sensing instruments are connected to an electronic data acquisition system. A surface observing station with an AWS can be fully automatic or a mixed system, allowing the addition of visual observations by a human observer. The main functions of an AWS are the conversion of the measurements of meteorological elements into electrical signals via sensors, the processing and the transformation of these signals into meteorological data and the recording and/or the transmission of the resulting information.

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. Data loggers are sometimes used as the acquisition equipment of the system and they are considered as a part of an AWS.

1.1.2 Purpose

The Minamata Convention on Mercury of the United Nations Environment Programme (UNEP) came into force globally in August 2017, and bans all production, import and export of observing instruments (thermometers, barometers, etc.) containing mercury (UNEP, 2017). This agreement is a global treaty to eliminate the use of mercury to protect both human health and the environment from the adverse effects of mercury. As a result, national meteorological organisation must transition away from mercury-based instruments. For most countries this will lead to the replacement of conventional instruments containing mercury with electronic ones (see Volume I, Chapter 1, 1.4.2).

Automatic weather stations are also used for increasing the number and reliability of surface observations. This is achieved by:

(a) Facilitating an increase in the density of observing networks, by providing data from new sites, where people are not available to take observations, and from sites that are difficult to access or inhospitable;

(b) Supplying, for manned stations, data 24 hours a day;

(c) Increasing the reliability of measurements by using 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 and/or continuously;

(i) Compensating for the shortage in the number of observers;

(j) Eliminating mercury from stations.

While presenting many advantages there are drawbacks or complications that arise from the process of automation:

(a) AWS networks decrease (sometimes to zero) the number of observers, but increase the staff needed for the maintenance , inspections, the system and software design and update, the calibration of electronic instruments, etc.

(b) Require a more skilled workforce in the areas of telecommunications, IT infrastructure, metrology and engineering.

(c) Significant change in the nature or some observations that may impact on climate monitoring, for example the move from manual visual observations to automated measurements.

(d) The quality of some observations may deteriorate due to key parts of the measurement process not being automated (for example, cleaning of the dome of solar irradiance instruments, evaporation pans).

(e) For places where labour costs are low and technology expensive, the conversion to automation may not result in lowering of operational costs.

When considering conversion from manual to automated observations, careful consideration of the capability of staff, cost of infrastructure and maintenance and the various impacts on data quality and volume is advised.

1.1.3 Meteorological requirements

The general requirements, types, location and composition, frequency and timing of observations are described in WMO (2015a, 2015b).

The performance of today’s electronic is no longer a limitation factor to achieve the accuracy requirements given in Volume I, Chapter 1, Annex 1.A of this Guide. The measurement uncertainties associated with an AWS are mainly linked to the characteristics of the instruments themselves and their exposure.

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

As for any observation network, 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 for the planned system (WMO, 2017b).

The Guide to the Global Observing System (WMO, 2010) gives a list of functional specifications for AWS (Appendix III.1, meteorological variables and associated BUFR descriptors to be used), the basic set of variables to be reported by standard AWS for multiple users (Appendix III.2) and AWS metadata (Appendix III.3)

It is not sufficient 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 organizations 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) Develop detailed guides and documentation on the systems to support all users;

(f) Develop adequate programmes for preventive and corrective maintenance and calibration support of the AWSs and associated instruments;

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

With respect to the automation of traditional visual observations (present weather, visibility, clouds) Meteorological Services should understand, that the observational characteristics of an AWSs' systems are different from the observation capability of a human observer:

(a) The visibility measurement is representative of the instrument location (unless several visibility meters are installed), while a visual observation makes use a 360° field of view, but is limited by the available visual landmarks. This means, the automated measurement will have high precision for the specific location, but may not be representative of a wider area.

(b) The cloud cover is usually derived from the measurements of the cloud base height from a ceilometer, combined or averaged over a given period of time (10, 30 or 60 minutes), while a human observer has a larger view of the sky, at least during day. The automated measurement represents a line through the sky in the direction of the upper winds. This may not correlate with the instantaneous whole of sky observation by a human.

(c) A present weather instrument is not currently able to identify the full range of present weather codes that a human observer is able to report.

In essence, manual and automated observations of visibility, cloud cover and present weather are distinctly different. Therefore, the 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;

[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).

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

Where a proposed automatic station has a role in providing data for climatological records (or where consistency of the measurands is important), it is important for the integrity, homogeneity and utility of the datasets that the following areas be considered for action[6]:

(a) Ensure overlapping periods of comparable measurements between conventional and new automated instrumentation;

(b) Ensure proper documentation is available on differences between the old and the new site as well as on instrumentation changes (Metadata)[8];

The overlap time[9] is dependent on the different measured variables and on the climatic 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:

(a) Wind speed and direction: 12 months

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

(c) Precipitation: 60 months

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

1.1.4 System configuration

An AWS is usually not used as a stand-alone equipment. It is part of a system with three main elements:

(a) The local AWS and the sensing instruments connected to it;

(b) The local modem or interface used to connect the AWS to a telecommunication network;

(c) A central processing system fed by the data transmitted by all the AWS making up the observing network. This central processing system is usually connected to the WIS or to an Automatic Message Switching System linked to the WIS.

Therefore, an AWS cannot be considered independently of this environment (instruments, telecommunication and central processing system) which influences the role of the AWS, the distribution of the data processing, the quality control and the like.

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.

The proceedings of several international conferences on AWS give very valuable information on the state of the art; the implementation of AWS networks; the migration from manual to

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

[8] Note also WMO (2013), 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".

[9] Note also WMO (*2013*), 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".

automated measurements; technical aspects for communications and system design; quality control and quality assurance (for example, see WMO, 2017a).

An off-line AWS, that is a station recording data on site without any automatic transmission, is less and less used, because data are not available in real-time and it does not allow a fast detection of possible failure of the equipment. The wide offer of means of telecommunication pushes to recommend the use of real-time AWS, even for climatological data.

Since observing stations 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.

In practice, there exist several categories of AWS, though some equipment is able to cover several of these categories:

(a) Light AWS for the measurement of a single variable such as precipitation and/or air temperature, applicable for both for climatology and real-time use.

(b) "Basic" AWS for the measurement of "basic" meteorological measurements (typically air temperature, relative humidity, wind speed and direction, precipitation and, sometimes, atmospheric pressure).

(c) "Extended" AWS with the additional measurement of solar radiation, sunshine duration, soil temperature, evaporation and so forth.

(d) AWS with automation of visual observations: "basic" or "extended" AWS with automatic observation of visibility, cloud base height, present weather. Such stations are commonly named as AWOS or ASOS in some countries.

A wide range of low cost AWS, including associated instruments, can be bought off-the-shelf, mainly used by hobby meteorologists or private companies. More about low-cost AWSs can be found in the annex. To lower the price, the sensors are often integrated and third party instruments are not available. The sensors and the electronics are not designed to be calibrated independently. Therefore the uncertainty of the measurements is greater than that obtained with "professional" equipment. It is difficult to estimate the uncertainty, due to a lack of documentation and the inability to open the equipment. Such equipment does not yet satisfy the CIMO requirements.

All-in-one AWSs are also available, designed by several suppliers of professional meteorological equipment. They include a set of embedded sensors with adapted electronics and software. Price, compactness and ease of installation are the advantages of these all-in-one AWS, usually allowing the measurement of wind (with an ultrasonic instrument), air temperature and relative humidity within an embedded radiation screen, pressure and precipitation (by radar, detection of droplets hits or with a more classical tipping bucket rain gauge at the top of the instrument). But some instruments are difficult to calibrate and often poorly documented and all the parameters are measured at the same height, which is a strong weakness. If exposed at about 2 m, the wind measurement is very sensitive to the surface below; if exposed at 10 m to follow the recommendations concerning the wind measurement, other parameters are also measured at 10 m, which does not comply with the CIMO siting recommendations.

1.1.6 Telecommunications

The available means of communications on the sites composing the observing network are a key factor in the design and the specification of an AWS system/network. Many technologies may be considered: Public Switched Telephone Network (PSTN), leased lines, cellular networks, satellite transmissions, optical fibres, access to internet and use of a Virtual Private Network (VPN) through these supports. The primary technical question before designing an observing network is to identify the available means of telecommunication. It is also important to consider the life cycle of the envisaged telecommunication medium, as rapid changes are possible in terms of coverage, price (generally decreasing), but also in term of sustainability. Therefore, the AWS and network design should allow an easy change of the telecommunication modem or interface, both in terms of physical interface and software.

Information Technology (IT) security has to be considered, especially if internet is used as an interim media for the transmission of data and system's dialogue. VPN and other techniques may be used, associated with the framework of Machine to Machine (M2M).

The wide spread of telecommunication media and internet may allow the application of the concept of IoT (Internet of Things) to individual "intelligent" meteorological instruments, thus eliminating the need for an AWS. This concept is not yet used for meteorological instruments but will be available in the near future. With such connected instruments, the concept of an AWS could partly disappear on site, all the data acquisition and processing being implemented in the central system.

1.1.7 Networking

An AWS usually forms part of a network of meteorological stations, each transmitting processed data to a central network processing system by various data transmission means (see 1.1.6). 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 have to be 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.

1.2 SYSTEM CONFIGURATION

1.2.1 Telecommunication network

1.2.1.1 One-way communication

It is important to identify if the telecommunication media to be used with the AWSs' network is restricted to a one way (AWS towards the central system) or allows two-ways communications. When limited to one way communication, it is not known on the AWS side, if the data sent have been successfully received by the central system. Therefore, it is advisable to format the data messages with control codes allowing the receiver to check the integrity of the message. Correction codes may also be used, to cope with possible transmission errors. If the volume of the message allows it, it can be a good practice to transmit several times the same measurement (in the same message or in consecutive messages) to manage errors and missed receptions.

1.2.1.2 Two-ways communication

When the telecommunication network allows it, the AWS can receive an acknowledgement from the central system for the correct reception of the transmitted messages. This guarantees the transmission of all new data since the last data is successfully received by the central system. The quantity of the data to be transmitted can be optimized, without the need of introducing the transmission of redundant data in order to deal with missing messages.

The AWS may also receive commands from the central system, to change its configuration, the transmission intervals, to retransmit old data and so forth.

1.2.1.3 Satellite transmission

Many satellite telecommunication systems are available, some of them being able to cover any part of the world.

Aside their main mission of imagery and sounding, nearly all the geostationary meteorological satellites have a Data Collection Service (DCS), a transponder of messages from self-timed Data Collection Platforms (DCP) towards the ground centre for the exploitation of the satellite data. A DCP is a one-way transmitter, associated with an antenna oriented towards a geostationary satellite, connected to an AWS. The messages have to be kept short (few hundreds of bytes), because of the low speed transmission of the channel (either 100 bauds for standard or 300, 1200 4800 bauds for high rate, depending on the satellite and DCS) and the limited time slot allocated to each station. As the transmission frequency is shared by several DCPs, each DCP must respect its allocated time slot and needs a precise clock, now easily achieved by using a local GPS receiver. An AWS with a DCP typically transmits every hour, at a time slot and a frequency channel allocated by the satellite operator. The majority of the frequency channels are "regional" channels used by each single satellite, but "international" channels shared by all the geostationary meteorological satellites also exist, to be used by mobile platforms (buoys, ships), which can move seamless from the field of view of one satellite to another one. A major advantage of DCS is that DCP channels are available at no cost for meteorological, geophysical and hydrological messages, provided they are also made available through the Global Telecommunication System (GTS) and discoverable in the WMO Information System (WIS). A disadvantage is that a specific transmission terminal (the DCP) is needed, with few manufacturers due to the quite low number of users and that normalized modern telecommunication protocols (IP, FTP, HTTP) are not available at the DCP level.

More and more commercial satellite telecommunication services exist, based either on geostationary telecommunication satellites or on low earth orbit satellites' constellation. Aside voice services, the operators offer data transmission services, generally using standard telecommunication protocols (IP based) and allowing M2M services. The required modems are not specific to meteorological applications, adapted to many data acquisition systems and therefore, available at a quite low price. This allows the design of a system where the AWS and the transmission modem are functionally separated, thus allowing an easy change of the telecommunication modem during the life cycle of the system, to use the services of a new (less expensive) telecommunication operator, for example. Sometimes, the way to use the telecommunication service has to be optimized to minimize the transmission cost, often linked to the quantity of data to be transmitted.

1.2.1.4 Public Switched Telephone Network

A Public Switched Telephone Network is often available in developed countries, in populated area. It may be easily used for data transmission with a modem, allowing two-way communications with a central system. The connection may use either analogue signals (a modem generates standard modulation frequencies for binary codes) or numeric ones (Integrated Services Digital Network, ISDN). The connection to a central system can be made in several ways:

(a) A point to point connection, the central system having a modem or a pool of modems on a set of lines. A Remote Access Service may be used, allowing IP based protocols once the connection is established.

(b) An access of the local AWS to an Internet Service Provider, thus allowing the use of an internet link to connect to a central system. This eliminates the need for the central system to use a pool of modems. The use of internet needs to consider security aspects, both on the side of the AWS, but particularly on the side of the central system.

Many countries and telecommunication operators are announcing the end of PSTN (analogic and ISDN). The fixed networks of copper lines should not be abandoned, but can be used for IP based communications, with ADSL connection or other techniques. Nevertheless, ADSL needs to be close enough from a switchboard, so the end of PSTN may reduce the availability of a connection through a fixed line for isolated locations.

1.2.1.5 Cellular network

Cellular networks are developing more and more, leading to the end of PSTN, often being the primary telecommunication offered. The needed infrastructure is less expensive than a copper base network of fixed lines. Several generations of data services exist, with an increasing flow rate (GPRS, Edge, 3G, 4G and so forth). Considering the volume of meteorological observational data, a low rate is sufficient and it is preferred to have a better coverage rather than a higher flow rate. Many industrial modems are available, with a low power consumption and fully compatible with solar panels of a reasonable size. Technical specifications for operation under high and/or low temperature must be considered, since the modems are usually installed in the AWSs cabinet, and therefore subject to local atmospheric conditions.

Standard IP based protocols can be used (TCP, FTP, HTTP, etc.). Operators also propose special services for M2M transmissions, using dedicated VPN for the customer.

1.2.1.6 Remote connection to Internet or VPN

Satellite, PSTN, ISDN and cellular networks can be used for an IP connection to a central system, via internet or a VPN. Any other internet connection can also be used, such as optical fibers, Worldwide Interoperability for Microwave Access (WIMAX), TV cable and the like.

1.2.1.7 Other communication technologies

Leased lines can be used when a permanent connection is needed between the AWS and a dedicated user (for example, an aeronautic user needing one minute data in real time). Nevertheless, the offer of dedicated point to point lines is being replaced (by the operators) by IP based connections, using the available transmission network.

In area not covered by a PSTN or a cellular network, dedicated radio links may be used. But the allocation of a frequency band by the appropriate regulatory authorities may be difficult, due to the competition between radio-frequency bands users. Specific radio bands reserved for data transmission are available, with a limitation of the power of the radio transmission, thus limiting the distance to few hundreds of meters or kilometres. Such radio transmissions may be appropriate to connect a distant instrument to an AWS, for example at an aerodrome.

New technologies of Low Power Wide-Area Network (LPWAN) are emerging. An LPWAN may be used to create a private wireless instrument network, but may also be a service or infrastructure offered by a third party, allowing the owners of instruments to deploy them in the field without investing in gateway technology. The volume of data which can be transmitted is limited to few tenths or hundreds of byte, which may be compatible with hourly meteorological observations. The main advantages are: a very low power consumption of the transmitters (durability up to 5 years with a single battery) and a low cost, both in terms of hardware and telecommunication service.

1.2.2 Central processing system

The majority of AWS are connected to a central system, which can be functionally separated in two parts:

(a) A collecting platform, designed to collect data from the AWS.

(b) A processing platform, fed in data by one or several collecting platforms. This processing platform is the interface towards the users of the observational data.

The collecting function and the data processing in order to supervise the AWS' network are typical tasks of a Supervisory Control And Data Acquisition (SCADA) system. SCADA are used in many industrial processes, factories, any location where field devices (instruments) are needed to control and interact with a production process. The problematic of an observing network is not different: field devices (AWS + instruments), communication infrastructure, data collecting and control (of the observing network). Many commercial software packages used for collecting and monitoring meteorological observations are developed by SCADA editors. Systems developed by hydro-meteorological equipment manufacturers may be specific to their own data acquisition system (AWS) rather than being issued from a multi-purpose SCADA type software, but they have the same functionalities.

1.2.2.1 Collecting platform

A surface observing system is often composed of several AWS networks, covering various needs and often set up during successive periods. Therefore, it is seldom to have a homogeneous set of equipment; different types of AWS, of telecommunication media and of protocols are mixed. Each generation of stations (AWS+modem) is functionally linked to an associated collecting platform. For ease of use, it is possible to consider that each AWS type with a given telecommunication network is associated to a specific collecting platform. In case of multiple ways of telecommunication, a set of collecting platforms may exist. Depending on the software and hardware needed, these collecting platforms may be implemented in the same system or separately.

A collecting platform has a connection to the telecommunication network used. When modems have to be used (that is for PSTN, ISDN, GSM Data, etc.) a pool of modems is managed. The modems can be physical equipment (one modem = one equipment) or logical equivalents within a physical equipment, such as a Remote Access Server (RAS). When the number of incoming lines is smaller than the number of AWSs from which data need to be collected, which is generally the case, the system must be designed to share the lines. If the AWS is initiating the connection, it has to follow a 'telecommunication profile', including a calling schedule to share the lines with other stations. If the connection is initiated by the collecting platform, the AWSs can be called sequentially by the collecting platform. In any case, the collecting platform should check the operational status of each incoming line, in order to detect problems, such as silent lines, error rate of communications on each line, and the like.

More and more, telecommunication networks are used as a gateway to the Local Area Network of the network manager (using internet or preferably VPN Tunnels through internet). The advantage in this case is that the collecting platform has no modems to handle, that means the physical interface to the telecommunication network is managed by the telecommunication operator. Standard IP based protocol can be used, such as FTP transfers, emails, etc.

A collecting platform should monitor the communications with the AWSs' network, by checking the actual connections compared to the expected ones. Silent AWSs should be identified. Supervision tools should be implemented to offer a global view of the network status (for example, green dots for AWSs waited and received, red dots for AWSs waited and not received), with detailed information for each station (such as the time stamp of the more recent data received) and each connecting line (if any).

If the telecommunication network allows two-ways communications, the collecting platform is also used to configure the network and individual AWS, in particular in terms of transmission schedule, type of data to be collected, etc.

Security protections should be installed, to avoid unauthorized access to the system. They include use of firewalls, control of the calling IP address or the calling phone number for authentication.

1.2.2.2 Processing platform

Data coming from one or several collecting platforms are sent to a processing platform. The primary function of this platform is to provide the measurement data to the end users. It is also very important to use this platform to support the technical management of a network and to offer a technical supervision of the observing network. Various indicators may be used to help the network manager, such as:

(a) Percentage of missing values for the whole network, for each station, over an one-hour period, over a daily period, and the like.

(b) Alarms for missing values, for each measured parameter (such as air temperature, wind speed and direction, pressure).

(c) Alarms for doubtful or erroneous values after application of quality control checks.

(d) Voltage of each AWS's battery and alarms if voltage is too low (the voltage measurement may be not significant when the battery is in charge, for example by solar panel; night measurements or minimum daily value have to be used).

(e) Presence or absence of the main power (if present in the installation), in order to detect a failure such as the release of a circuit breaker, which could be hidden by a buffering battery.

(f) When smart sensing instruments are used, they often deliver service parameters, in addition to the desired meteorological variables. These service parameters are useful to detect or anticipate problems with the instrument (such as cleaning needed) and should generate alarms for the maintenance manager.

The typical operational functions of the processing platform are:

(a) The quality control of the "raw" data. The quality control algorithms may be partly split between the AWS itself and the central system.

(b) The calculation of meteorological parameters from individual measurements, for example the calculation of dew point temperature from measured air temperature and relative humidity. This calculation may be shared between the AWS and the central system.

(c) When the data processing can be implemented either at the AWS's level or at the central server's level, it is recommended to choose a central implementation, where software development and updates are easier to implement. Nevertheless, some data processing by the AWS itself may be needed in case of a local use of the observation (for example a local observer or an aerodrome), unless the telecommunication network used is considered as compatible and safe enough to download the local observation from the central system to the tower control. A local aeronautic usage is a special case which may need local data processing in order to supply the Air Traffic Control with local observation data, through aeronautical local reports.

(d) The coding of standard messages to feed an Automatic Message Switching System (AMSS), usually the source of data for the NMHS. Standard messages in a format needed for the distribution on the GTS may also be formatted in the AMSS, if not directly formatted in the central processing platform. For surface observations, alphanumeric messages (SYNOP) are replaced by self-described codes (Table-Driven Code Forms, TDCF). BUFR templates have been designed for surface observations (WMO, 2016).

1.2.3 Instruments

All modern sensing instruments are suited for use with an AWS. Instruments are described in Volume I of this guide. Some constraints for their use with an AWS are listed below:

(a) They have to be robust and with minimal maintenance and cleaning required, as many sites have no local maintenance staff.

(b) They should be easily interchangeable, with little or no change needed in the AWS configuration and calibration.

(c) Their connection to an AWS shall be fully documented in terms of cabling, power supply (range, power consumption with and without heating, warming up time if the power supply is switched on and off to lower the power consumption, etc.) and transfer function (relation between the electrical output and the meteorological parameters).

Instruments with an analogue output generally deliver only the meteorological variable measured. Those with a digital output deliver the meteorological variable that is measured, but also offer additional service parameters, useful to monitor the instrument's state and to optimize its maintenance. It is important that the service parameters are also taken into account by the system (AWS + central system).

Radiometers (pyranometers, pyrheliometers, etc.) are a special case. The majority of these instruments are using a thermopile that is often directly connected to the AWS. Therefore, the calibration factor of the thermopile has to be applied behind the sensors, either in the AWS itself or in the central system collecting the data. When a radiometer is changed on site (at least for a regular calibration), the associated calibration factor has to be changed accordingly in the system. The experience shows that errors sometimes occur, due to human fault (change of the instrument or sensing element without updating the calibration factor at the same time). Some models of radiometers include a microprocessor to convert the analogue signals into numeric digital values within the instrument itself; the calibration factor is then included in the instrument and updated after calibration. Such an instrument is fully interchangeable, with no needed update of a calibration factor in the system, which reduces possible human errors.

Wind measurements (mean values, gusts) need a high acquisition rate (see Volume I, Chapter 5, 5.8.2) and a calculation of mean values and gusts over larger periods (10 minutes for synoptic use, 2 minutes for local aeronautical use). The calculation can be carried out on the AWS itself, but many modern anemometers have an embedded calculation of the wind parameters. An advantage is the reduction of the data acquisition rate at the level of the AWS, with a typical one minute update of wind data, rather than a data sampling of several Hz.

It is highly recommended that barometers connected to an AWS have a digital output, to avoid additional uncertainty in the conversion of an analogue signal into pressure. Indeed, using a barometer with an analogue output needs a high quality analogue to digital converter, to achieve the recommended measurement uncertainty and performance requirements specified in Volume I, Chapter I, Annex 1.A.

It can be desirable to double (or even triple) some instruments. This approach can minimize the probability of missing values in case of instrument failure and/or introduce measurement redundancy in the system to detect possible instruments' drift. The difference between two instruments indicates a drift of at least one of them; if three instruments are used, it becomes possible to identify automatically which instrument is drifting and choose to exclude its values. This procedure of using multiple sensing elements is used within some instruments. Several commercial models of barometers are available with one, two or three cells.

1.3 Automatic weather station hardware

Several designs of AWS exist:

(a) A stand-alone equipment specifically designed for meteorological measurements. Depending on the manufacturer, it is designed to accept a given list of instruments. Therefore, it may be difficult to use or add new instruments that are not supported. Being designed for meteorological measurements by the meteorological industry, there is good chance that all the needs may be fulfilled and therefore, the restriction for adding new instruments may not be a problem.

(b) An industrial data-logger, not specific to meteorological measurements. An advantage is a potential higher versatility, with analogue inputs, counters, etc. Also, the cost may be lower than dedicated equipment. In some cases where meteorological instruments have stringent characteristics, such as the low output voltage of a radiometer using a thermopile, it may not be suitable. Wind measurement is also a special case, if the data logger must derive wind parameters with a sampling rate of several Hz.

(c) Some designs split the data acquisition between separate electronic boxes; some of them associated to one instrument to digitize its analogue output, being as close to the instrument as possible. These interface boxes dialog with a central processing unit.

(d) In some other designs, digital or smart instruments and analogue instruments digitized by an electronic interface are directly connected to a laptop, Personal Computer (PC) or an industrial PC, installed either indoor or directly in the field. This allows use of the hardware and software of standard microcomputers. Nevertheless, cabling and surge protection should not be neglected.

(e) When a human observer must interact with the AWS, for example, to enter visual observation, a local PC is usually used, both to locally display the observations and to edit the visual observation. Such a local computer may also deliver the local observation data to local users, such as aeronautic users.

The layout of an AWS typically consists of the following:

(a) On a standard observing area (see Volume I, Chapter 1, and WMO, 2013), a series of automated instruments sited at the recommended positions and interconnected to one or more data collection units using interfaces, sited for not affecting each other and connected to a central processing unit (CPU) by means of shielded cables, fibre optics, or radio links;

(b) A CPU for instrument 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) A modem or an interface to the telecommunication network used for the transmission of data towards a central system;

(d) A stabilized power supply providing power to the various parts of the station;

(e) For specific applications, local terminals for the manual entry and editing of data, display devices and printers, or recorders are added to the station.

It is a good practice to design the system on a modular basis in order to adapt it to new instruments, new variables, changes in the telecommunication network, and so forth. Nevertheless, a high level of modularity may increase the cost of the equipment, therefore it is important to anticipate the possible future changes as much as possible, in order to select a good compromise between modularity and a compact and standard design (across the whole network). Due to the short life cycle of many telecommunication networks, it is highly recommended to use an AWS with a modular telecommunication terminal.

For the maintenance of the AWS, the design should facilitate field work for preventive and corrective maintenance (for example, a regular replacement is needed for instruments that need to be calibrated). Again, modularity is a solution or the possibility to easily replace the whole AWS, if it is a stand-alone design. Connectors with a keyed position may be preferable to wires directly connected to a terminal strip.

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 (built-in test equipment). For example, 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 (if temperature and humidity ventilated screens are used), A/D converters, and heaters. Status information should be monitored as well, and transferred to the central server unit for an automatic quality-control and maintenance purposes.

1.3.1 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. 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 these functions are carried out by one microprocessor-based system installed in a weather-proof enclosure as close to the instruments as possible, or at some local indoor location. If the unit is located near the instruments, 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 main power supply and operated as if it was 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, different units may also execute the different functions of the CPU. In such cases, each unit has its own microprocessor and relevant software. The units can be installed at different places in the station and can communicate with other units 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 instruments 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. Low power wireless links are also usable, some frequency bands being dedicated to data transmission without a specific authorization procedure, assuming a low power emission. These units can consist of one instrument (for example, an intelligent instrument such as a laser ceilometer), a number of similar instruments (for example, thermometers), or a number of different instruments, such as analogue instruments connected to a data logger in the field.

The data-processing hardware is the heart of the CPU. 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 first AWS were equipped with 8-bit microprocessors and limited memory (32 to 64 kbytes). Systems using 16-, 32- or 64-bit microprocessors surrounded by a considerable amount of solid-state memory are now a standard. These AWOSs provide more input/output facilities which operate at much higher processing speeds and are capable of performing complex computations. Together with this hardware, sophisticated software is applied. In addition to the random access memories (RAM) for data, many systems have access to a read only memory (ROM). Some of the range of ROMs include non-volatile programmable read-only memories (PROMs) for program storage. The CPU often uses non-volatile random-access memory (NOVRAM or EEPROM, also known as flash memory). System's configuration constants can be modified and the data stored safely during power failures. The AWS software may be downloaded from a local connection or even from the central system. The size of today's available memory is large enough to memorize tenths or hundreds days of observation data.

Real-time clock: The CPU of an AWS needs 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 ensure correct read-outs, sample intervals and time stamps. A clock stability better than one second over a 24 h period is recommended and achievable. The real-time clock should also be synchronized either with the GPS signals or by a central reference clock, available through the telecommunication network (such as a time server over the internet).

1.3.2 Sensing instruments' interface

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

(a) Signal-conditioning hardware for preventing unwanted external sources of interference from influencing the raw instrument 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.

Low-pass filtering: Filters are used to separate desirable 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 desirable signals do not exist. These filters may be realized either by analogue techniques (electronic) or digital filters.

Amplifiers: Analogue instrument signals can vary in amplitude over a wide range. The analogue-to-digital (A/D) converter (ADC), 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 desirable amplitude. Amplifier modules are sometimes employed to standardize the voltage output of all instruments to a common voltage, for example 0–5 voltage direct current, in order to use a common high performance ADC.

Resistances: Special modules are used to convert resistances, such as of platinum thermometers, into an output voltage signal by providing the necessary output current. Temperature measurement is particularly susceptible to the method of conversion from resistance to temperature. Lower quality systems may use a two or three wire approach, while the better designs use a four wire and switch the measurement direction. This allows for compensation for any lead resistance.

Data-acquisition function

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

To accommodate the different types of meteorological instruments, 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 instruments and is determined by the type of application.

Analogue inputs: The number of analogue channels depends on the basic design of the equipment. 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 instruments, such as temperature, radiometers and humidity instruments, deliver a voltage signal either directly or indirectly through the instrument-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 (ADC). Software can control these switches to select any one channel for processing at a given time. In some AWSs' designs, a separate ADC is used for each channel. The ADC 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 0.0015 % of the A/D full range of scale. In the first AWSs generation, offset and gain of amplifiers and A/D converters had to be adjusted by means of potentiometers. Modern electronics use fixed, stable and precise reference elements, which prevent any manual adjustments of the electronic chain.

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 instruments with parallel digital output (for example, wind vanes with *Gray* code output).

Pulses and frequencies: The number of channels is generally limited, because few instruments deliver such signals. Typical instruments are anemometers and (tipping-bucket) rain gauges. Use is made of low- and high-speed counters accumulating the pulses in CPU memories. The counters should use analogue or digital filters to avoid unwanted pulses, such as electro-magnetic spikes.

Serial digital ports: These are individual asynchronous serial input/output channels for data communication with intelligent instruments. The ports provide conventional inter-device communications over short (RS232, several metres) to long distances (using of a pair of modems or RS422/485, several kilometres). Different instruments or measuring systems are sometimes connected to the same line and input port, each of the instruments being addressed sequentially by means of coded words. Unfortunately, there is no universal standardization of the dialogue protocol with the instruments, except protocols or formats defined by some manufacturers for their own equipment. SDI-12 (Serial Digital Interface at 1200 baud) is an asynchronous serial communication protocol for intelligent sensors that monitor environment data, which is supported by some instruments and AWSs.

Ethernet connection: Some instruments are quite autonomous and are able to communicate either with the AWS or even with a central system (IoT) using IP based protocols.

1.3.3 Cable connection and surge protection

Connections: Cables and a mechanical connecting system are necessary for connecting the instruments to the data-acquisition electronics. The cables may be connected directly to the data acquisition system via a terminal strip, with screwed connections or solder connections or self-locking connections. Packing glands are often used to cross the enclosure box of the AWS. Another solution is to use a pair of connectors, with a fixed one on the enclosure box (and connected to the electronics). The advantage is the possibility to easily unlock an instrument and its cable for replacement. The type of connection and the location of possible connectors should be selected to facilitate the field operations, having in mind the expected periodicity of instrument's replacement (for example, for regular calibration).

Instrument cables: Electrical signals from the instruments 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. 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 particularly from lightning. Protection modules against surge should be easily replaceable. They are often a one shot protection, therefore their status should be easily testable, the best solution being a visual mark of their status. A basic rule for good surge protection is to insure an equipotential bonding of the different electrical masses of the system, including the shield of the cables. Ground connections should be kept as short as possible, in order to facilitate the path of high voltage spikes through these ground connections rather than through the electronics. The ground of the AWS and its peripherals (including instruments) must be connected to the ground network of the site (if available). If not available, a local grounding electrode and associated buried grounding network must be installed, in order to offer the best path to current surges.

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 (modems) not only isolate, but also convert the inputs into standard voltage levels that can be read by the data-acquisition equipment. The galvanic isolation allows to avoid the use of copper lines to realize the equipotential bonding between distant points (copper wires and trenches over hundreds of meters are costly). Nevertheless, surge protection of a digital line remains necessary, because high frequency spikes are able to cross transformers, even with galvanic isolation.

1.3.4 Power supply

The design and capability of an AWS depend critically on 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, consideration should be given to the use of 12 V direct current power supply. Where mains power is available, the 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. The capacity of the buffer batteries depends on the mean power consumption of the system (AWS+instruments, including heating+modem) and the accepted duration of missing mains power.

Automatic weather stations deployed at remote sites where no mains power is available must rely on batteries nearly always sourced by solar cells or other power sources, such as a diesel generator and wind- or water-driven generator. However, such low-power systems cannot, in general, support the more complex instruments required for cloud height and visibility measurements, which require large amounts of power. Furthermore, AWSs with auxiliary equipment such as heaters (for example, anemometers and rain gauges) and aspirators can also consume considerable amount of 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 a support from a backup supply, for at least the system clock, the processor and any volatile memory that may contain recent data needed to restart the station automatically. It is also a good practice to shut down the system when the voltage of the batteries falls below a fixed threshold, in order to protect the batteries which do not support a deep discharge.

It is important that the system be designed to measure and report the status of the power supply, for example battery voltage, charging current delivered by solar panels and presence or absence of the mains power. These status parameters should be transmitted to the central system, to optimize the maintenance operations and to alert the maintenance staff of any problem. Mains power is protected by a circuit breaker, which may trip off in case of surge. On an isolated site, a staff displacement just to reactivate a circuit breaker may be very costly and time consuming, so it can be useful to install a circuit breaker with a possibility to reactivate it by remote command, unless the tripping off is linked to an electrical circuit default, to be fixed.

1.3.5 Enclosure protection

The electronics part of an AWS has to be protected from the outside atmosphere, unless it is installed indoor. A protective box is highly recommended. It should be large enough to allow an easy access to the internal equipment, unless the system is designed for replacing the whole equipment, including protective box, in case of failure.

The protection against water and condensation should be made by one of the two following techniques:

(a) The protective box is completely sealed and not designed to be opened in the field. It should then include an internal bag of hygroscopic salts.

(b) The protective box is aerated with gills fenced in against the entrances of insects. The box should be designed to avoid the entry of water when opening its door.

The material should be chosen to avoid corrosion, especially close to the sea side. A metallic box helps in protecting the electronics against surge.

1.3.6 Installation structure

When installed outside, the AWS box(es), the instruments, and the terminal distribution of the mains power or the solar panels have to be installed on the basements. The installation structure must not be neglected, as it can be expensive. It is a good practice to define standard accessories for the installation of an AWS and its' components. Supporting structures may be proposed by the AWS's manufacturer. It is important to check that the instruments and other equipment are not interfering each other; in particular, the clearance rules described in the siting classification (see Volume I, Chapter 1, Annex 1D of this guide) should be followed by the design of the supporting structure.

Some concrete basement may be necessary. An alternative may be the use of metallic ground screws, designed to support pylons, fences, etc.

The need for a local earth electrode and buried earth network must be considered.

Depending on the location of the station and the surrounding risks (for example, animals and humans), fencing of the observing area may be necessary.

1.4 AUTOMATIC WEATHER STATION SOFTWARE

The three main designs of AWS have different frameworks for the software:

(a) A stand-alone AWS uses specific software developed by the AWS's manufacturer. Few or no modifications are possible by the end user, except some configuration choices. But the AWS is often delivered ready to be used. Modifications in the AWS functionalities have to be implemented by the manufacturer itself.

(b) An industrial data-logger is usually designed with a command language, to allow the user to configure the equipment according to his instruments and needs (of course in the limits allowed by the data logger design). The software configuration may be more complicated and realized by the data-logger distributor, or by a third party integrator, or by the user itself.

(c) The software of a laptop or industrial PC with digital instruments directly connected to it is less dependent on the hardware and may enable use of more standard tools and languages. Some NMHSs develop their own software with this type of AWS configuration.

The software is a major part of the AWS. Unless great care is taken in the preliminary design and strong discipline maintained while coding, complex software readily becomes inflexible and difficult to maintain. Minor changes to the requirements, such as those often induced by the need for a new instrument, 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 hardware configuration and comprising all software to develop and run application programs.

Discussion of the design of algorithms for synoptic AWSs can be found in WMO (1987) and for the processing of surface wind data in WMO (1991). Information on the algorithms used by Members is available in WMO (2003).

1.4.1 Operating system

The operating system of a stand-alone AWS or a data-logger is generally very specific to the hardware and based on industrial real-time embedded operating system (so-called firmware), thus turning the CPU into a sort of black box. Sometimes the operating system is more classical, such as a Unix based system. The user can execute only predetermined commands and, as a consequence, entirely depends on the manufacturer in the event of malfunctions or modifications.

When a laptop, PC or industrial PC is used as a CPU, its operating system is more standard, such as a Unix based system or a Windows operating system. The full range of administration tools and communication layers are therefore available. In return, such a system is more opened to hackers and IT security protections have to be set and software updates and upgrades have to be applied regularly.

1.4.2 Application software

The processing functions that must be carried out by the CPU, the instrument 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, some or all of the following operations are required: initialization, sampling of instrument output, conversion of instrument output to meteorological data, linearization, averaging, manual entry of observations, quality control, data reduction, message formatting and checking, and data storage, transmission and display. Quality control may be performed at different levels: immediately after sampling, after deriving meteorological variables, after the manual entry of data and message formatting, or in the central system (quality control is often split between the AWS itself and the central system). If there are no data quality control and message content checks, the AWS data are likely to contain undetected errors. While linearization may be inherent in the instrument 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.

1.4.2.1 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 requires first a number of specific parameters, such as those that are related to the station (station code (ID) number, altitude, latitude and longitude), date and time, physical location of the instrument in the data-acquisition section, and type and characteristics of instrument-conditioning modules. Conversion and linearization constants for instrument output conversion into meteorological values, as well as absolute limits and rate of change limits for quality-control purposes and data buffering file location, are also included. 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 most recent 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. The central system (typically a collecting platform) should be able to report the full set of initialization parameters of each AWS, for network and maintenance management.

1.4.2.2 Sampling and filtering

Sampling is the process of obtaining a discrete sequence of measurements of a quantity. To digitally process meteorological instrument signals, the question arises of how often the instrument outputs should be sampled. It is important to ensure that the sequence of samples adequately represents significant changes in the atmospheric variable being measured. Generally accepted rule of thumb is to sample at least once during the time constant of the instrument. However, as some meteorological variables have high frequency components, proper filtering or smoothing should be accomplished first, by selecting instruments with a suitable time-constant or by filtering and smoothing techniques in the signal-conditioning modules. More details are presented in Volume V, Chapter 2.

Instruments needing a high frequency sampling often have their own embedded microprocessor to calculate the relevant meteorological parameters, thus reducing the task of the AWS. A typical example is an anemometer with a recommended sampling frequency of several Hz.

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 instruments with short time-constants make averaging a most desirable process for reducing the uncertainty of reported data.

Volume I, Chapter 1, Annex 1.A recommends that "instantaneous" values of most of the meteorological variables be a 1 min average (except for wind and visibility).

1.4.2.3 Raw-data conversion

The conversion of raw instrument data consists of the transformation of the electrical output values of instruments or signal-conditioning modules into meteorological units. The process involves the application of conversion algorithms sometimes using constants and relations obtained during calibration procedures.

An important consideration is that some instruments are inherently non-linear, namely their outputs are not directly proportional to the measured atmospheric variables (for example, a resistance thermometer). Other measurements are influenced by external variables in a non-linear relationship (for example, some pressure and humidity instruments are influenced by the temperature). While some instruments may be linear or incorporate linearization circuits, the variables measured are not linearly related to the atmospheric variable of interest (for example, extinction coefficient, but not visibility or transmittance, is the proper variable to be averaged in order to produce estimates of average visibility). Consequently, 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 instrument 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 average only linear variables. More details are presented in Volume V, Chapter 3.

The knowledge of raw data values may be very valuable for the maintenance staff, therefore considerations must be given to the transmission of some raw data values towards the central system. A typical example is the use of analogue relative humidity instruments. If a 0-1 V output hygrometer is used, 0 V stands for 0 % and 1 V for 100 % of relative humidity, the maximum operational value. But such a hygrometer might output a raw value above 1 V, for example, 1.03 V. Obviously it is not an operational value of 103 % of relative humidity, but it may be an instrument drift or a value inside the tolerance limits of the instrument. In the conversion to meteorological units, these 1.03 V should be limited to 100 %, with a threshold limit (such as a value above 1.05 V is considered as an invalid value). But for the maintenance process, it is important to know that these 1.03 V have been reported by the hygrometer, it may be an indication of an instrument drift.

1.4.2.4 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 instruments are provided at the station. These typically include present and past weather, visibility, cloud layers, state of the ground and other special weather phenomena. If some instruments for these parameters are installed in the system, they should be considered as an aid for the observer during the periods with human observation. That means that a terminal system (often a PC) used for manual entry should also display the measured parameters for the local human observer.

1.4.2.5 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. For example, data reduction is the calculation of dew point temperature 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 (for example, temperature), total amounts over specific periods of time, from minutes to days (for example, rain), means over different time periods (for example, climatological data), and integrated values (for example, radiation). These variables or quantities can be computed at the AWS's level, or in a central processing platform, from instantaneous data or extremes, and total amounts calculated over small periods (for example, one hour). A tendency of recent systems, when the telecommunication network allows it, is to collect centrally one minute data (instantaneous values and meteorological variables calculated every minute, for example wind parameters) and to process these data in a central processing platform. This allows a greater flexibility in the development and upgrade of the processing software, and simplifies the AWS software. One minute data may greatly help the maintenance team to detect and identify possible measurement problems (see 1.2.2.1).

The algorithms used to derive values in the AWS are as important as the choice of instrument. Small and subtle changes can be introduced over time that can have significant impacts after. A register of algorithms as well as software versions should be kept as a part of the metadata for the AWS. Where the algorithm is created in house, it is wise to document the process and to develop data test sets so that changes to software can be consistently checked in the future.

CIMO is involved in a regular programme to survey and standardize algorithms for all variables. The results are published in the WMO (2003). See also the corresponding Chapters of Volume I of this guide for details on the meteorological variables.

1.4.2.6 Local data storage

Meteorological data are regularly transmitted to a central system in nominal conditions. Nevertheless, a break in the telecommunication scheme may occur or data can be lost in the collecting process. Therefore, it is important that the local AWS has a local data storage and an associated procedure to access the data. Local data storage is no longer a problem with flash memory components. The AWS software generally manages the data in a circular memory over a given period, replacing old data by new ones. The size of data storage shall be compatible with the accessibility of the observing site, up to several months for a very isolated site. It may be the same set of data that are normally transmitted to the collecting platform. If necessary, in order to reduce the memory size needed and/or to facilitate the procedure of recovery of the data, hourly instantaneous variables and hourly statistical variables (extremes, totals) may be also stored locally.

The procedure to access the local data can be:

(a) A transmission of old data when the telecommunication infrastructure becomes available again.

(b) A local transfer of the data with a portable terminal locally connected to the AWS, during a maintenance operation.

(c) A local recuperation of a memory card (for example, a flash memory card) during a maintenance operation.

The recovery procedure must be accompanied by a mechanism of complementing the central data base with the old recovered data.

1.4.2.7 Message coding

Functional requirements often stipulate the coding of meteorological messages in accordance with WMO (2016). Message coding algorithms should not be underestimated and require noticeable efforts not only for their development but also for updating when formats are altered by international, regional and national regulations. The transition from alphanumeric codes (typically SYNOP) to Table-Driven Code Forms (BUFR or CREX) facilitates the update of the content of observing messages.

The coding of standard messages is generally easier in a central processing platform, where more computing capacity and also more standard software tools are available (free BUFR coding software is available from several sources). Therefore, the majority of network of AWSs are designed for a central coding in standard codes. The format of the messages between an AWS and the collecting platform varies. It should also be based on the principle of a table driven code, allowing the upgrade of the transmitted variables without needing any changes in the transmission layers. In addition to the requested meteorological variables, additional service data should be coded and transmitted, such as service data from smart instruments, battery voltage, raw data from some instruments (for example, the raw value output by a 0-1V hygrometer, as described in 1.4.2.3). As such parameters are very specific to the AWS design and not listed in BUFR tables, it is an additional reason to code standard WMO messages at a central level.

1.4.3 Remote diagnostics and maintenance

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 instrument, AWS reconfiguration after the replacement of instruments or models, resetting of system parameters, telecommunication tests, entering new calibration constants and so forth. In general, maintenance and calibration is conducted in an off-line mode of operation, temporarily interrupting the normal station operation.

Some of these functions may be available also on line, via the data collecting system. Any function allowing a distant diagnostic should be encouraged in the design of the system, in order to reduce maintenance costs. In practice, transportation of maintenance staff to the measuring site is a huge percentage of the maintenance cost and any on-line possibility is welcomed (for example, transmission of service parameters, resetting a circuit breaker and downloading a new software version for the AWS or one of its component).

1.5 QUALITY CONTROL

The purpose of quality control at an AWS is to minimize automatically the number of inaccurate measurement data and the number of missing data by using appropriate hardware and software routines. Both purposes are served by ensuring that each calculated measurement data are derived from a reasonably large number of quality-controlled data samples. In this way, samples with large spurious errors can be isolated and excluded, while the computation can still proceed, not being contaminated by that sample.

Quality control ensures 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.

In modern AWSs, the results of data quality-control procedures applied to instruments which reveal the reasons why a measurement is suspicious or erroneous and of hardware self-checks by built-in test equipment are stored in appropriate housekeeping buffers. The transmission of these results and the visual display of these status indicators form a very handy tool for continuous monitoring of the network, and during field or remote maintenance. The transmission of housekeeping buffers, as an appendix to the routine observational message, or a separate bulletin, or as a clocked or on-request housekeeping message, from a network of AWSs to a central network processing system, is highly recommended to support the maintenance of meteorological equipment.

Real-time procedures for the quality control of AWS data are highly advisable, and detailed recommendations exist in Appendix VI.2 of the Guide to the Global Observing System (WMO 2013) and in Volume V, Chapter 1 of this Guide. The following is a brief summary of the guidelines available in WMO (2013).

Intra-instrument checks: Each instrument sample is checked at the earliest practical point in the processing, taking into account instrument and signal-conditioning response functions, for a plausible value and a plausible rate of change. Some additional tests are possible, for example:

(a) If barometers with 2 or 3 pressure cells are used, the difference between cells could generate an alarm if this difference is larger than a given threshold (for example, 0.3 hPa).

(b) If relative humidity is measured by a hygrometer, the maximum daily value indicated by the instrument could be calculated (see 1.4.2.3). This parameter analysed over long periods may help to identify clues of a possible drift at the saturation point (100 %).

Plausible value: 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 instruments and data-acquisition hardware. Additional checks against limits which are functions of geographical area, season and time of year could be applied. The checks help identifying erroneous or suspicious values.

Plausible rate of change: Checks for a plausible rate of change from a preceding acceptable level. The test settings depend on the observed parameter and the atmospheric phenomena which could influence it. It also depends on the instrument characteristic (for example, time constant and persistency).

Minimum required variability of instantaneous values: Checks that the instrument is still reacting on atmospheric changes. A long period without significant change in the measured data is an indication for malfunctioning (for example, a cup and vane anemometer starting to jam). Variability and time response are dependent on the measured parameter, and on the instruments characteristic.

Maximum allowed variability of instantaneous values: Identical to the previous.

Number of valid samples in a period: This determines the validity of the average and its suitability for use in further calculations.

Inter-instrument checks: It is possible to make internal consistency checks of a measured variable against other measured variables, based on established physical and meteorological principles, for example, dew point temperature 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 problem with wind-direction instrument.

Technical monitoring: Technical monitoring of all crucial AWS components.

Message checking: For AWSs equipped with software for directly coding messages and for transmitting the messages over the GTS, it is of vital importance to execute all the above checks very carefully. In addition, compliance with regulations concerning character, number, format, and so forth, should be controlled. Proper actions are to be considered when values are classified as suspicious.

For AWSs associated with a central collecting and processing system, the quality control checks are split between the AWS software and the central software. If the raw data samples are not transmitted to the central system, only the checks using the raw data samples must be implemented inside the AWS. When one minute data are transmitted centrally, the other quality control checks should be implemented in the central processing system.

1.6 Automatic weather station siting considerations

The proper siting of an AWS is a very difficult matter and much research remains to be done in this area. The general principle of siting 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 Volume I, Chapter 1, Annex 1.D, as well as in WMO (2010, 2014, 2017a).

The surrounding area and the obstacles close to the instruments should not decrease the representativeness of the measurements. The site classification defined in Volume I, Chapter 1, Annex 1.D of this guide should help in choosing a representative site: the ideal location should be a site of class 1 for all the measurements, but compromise are sometimes necessary, because criteria and factor of influences are not identical for all atmospheric parameters. The network designer should define the maximum classes allowed for selecting a measuring site and a derogation procedure in case of special difficulties to find a site following the selected rules. A split of the station, with delocalized instruments, might also be considered. The current available technology allows it relatively easy (see 1.2.1).

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 in the choice of the site. Security measures (against lightning, flooding, theft, vandalism, and so forth) are to be taken into account and the stations must be able to withstand severe meteorological conditions. The cost of providing systems capable of operating under all foreseen circumstances is high and may be prohibitive. It is essential to obtain a thorough understanding of the working environment anticipated for the AWS, before specifying or designing an AWS. 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.

1.7 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.

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. With the increasing reliability of the electronic components of an AWS, preventive maintenance, including services and instrument calibration, becomes 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 of operation. Repairing costs and costs of different components often rapidly increase after a system is no longer in active distribution, thus making necessary to replace modules by new ones with different technology, because exact replacements are seldom found, for example, transferring programs and operating systems from one processor to another, introducing modular changes for system reliability, connecting with new telecommunication systems, and so forth. In order to reduce the costs for this type of maintenance, it is desirable to establish widely accepted standards on equipment and interfaces, as well as on software, and include them in AWS technical specifications.

The installation of a network of automatic stations must not be seen as a one shot investment. It is essential to organize maintenance according to a rational plan that details all the functions and arranges them in order 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 instruments or other modules in the field because conditions might not favour effective work. It is recommended that corrective maintenance in the field is carried out by specialized technical personnel from a regional or national centre, depending on the size of the country. Simple preventive or corrective maintenance can be done by a local observer (when available) or a local design operator. The regular 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 instruments 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 instruments to support the maintenance of the stations in their area. They also need the necessary access via telecommunication network to the AWSs, the backbone network, and, possibly, the central servers. 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 are capable of detecting and eliminating complex problems in instruments, 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 of utmost importance 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.

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 countries. 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 supporting functions. Such support could, for example, be negotiated as a 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 Volume V, Chapter 1.

1.7.1 Service levels

A service level for maintenance should define the maximum delay to diagnose a problem and a maximum delay to fix it. An example of such maximum delays, used by one national meteorological service, is given below:

(a) Four hours on a very large aerodrome. This implies a local maintenance team is available 24 hours a day and spare parts are available locally.

(b) 15 hours on important aerodrome or synoptic station. 15 hours stands for a rapid maintenance action in the day of the failure detection or the next morning if the failure occurs during the evening or the night. This implies maintenance staff available close to the site (for example, at less than 2-3 hours of driving), with spare parts available and working hours, every day of the week.

(c) Two or three days on other stations. This allows longer driving displacement and/or getting spare parts from a distant location (for example, a national centre) and staff only during working days.

(d) Five days for lower priority stations.

Service levels should be defined during the network definition, taking into account the users' needs, the maintenance organization, the distances between the maintenance centres and the observing stations, and the cost of spare parts stocks. The result is necessarily a compromise between the users' expectations and the human and the recurring costs. Different service levels may be defined for different stations.

1.7.2 Calibration and site inspection

Instruments, in particular AWS instruments with electrical outputs, drifts in time and, consequently, regular inspection and calibration are needed. In principle, the calibration interval is determined by the drift specifications given by the manufacturer and the required uncertainty. WMO international instrument intercomparisons also provide some objective indications of instrument 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. For more detailed information on calibration techniques and methods, refer to the different chapters of Volume I and to Volume V, Chapter 4,.

Initial calibration: Appropriate calibration facilities and instrumentation should be available prior to the procurement and installation of AWSs, in order to enable verification of the specifications given by the manufacturer, testing the overall performance of the station and inspection if transportation has affected the measuring characteristics of the equipment.

Field inspection: The periodic replacement or comparison of AWS instruments with travelling standards at the station is an absolute requirement to monitor the performance of the instruments. Travelling standards having similar filtering characteristics to the AWS measuring chain and with a digital read-out are preferred. In many countries, two travelling standards of the same type are used to prevent possible problems with change of accuracy due to transportation. In order to be able to detect small drifts, the travelling standards should have an uncertainty that is much lower than the relevant station instrument and should be installed during the comparison process in the same environmental conditions as the instruments 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. The period between inspection visits should be determined by the drift characteristics of the instruments. As experience with the instruments is increased, deviation adjustment of the schedule can be justified.

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, if uncertainty deviations are detected.

Field inspections should also be used to control the state of the observing site:

(a) The site environment (obstacles such as trees, vegetation, buildings, etc.) in order to detect possible changes in the siting classification (Volume I, Chapter I, Annex 1.D). Photos are enormously useful for monitoring site changes.

(b) The state of the vegetation in the instrument field and vegetation cutting if necessary.

(c) The state of all infrastructure: fencing, supporting structures of the AWS and the instruments (for example, corrosion).

(d) The state of the power supply system: cleaning of solar panels, periodic change of batteries.

(e) The state of the surge protections.

(f) The cleaning of instruments, as appropriate.

(g) Any other task to be defined, as appropriate (according to the equipment user manual provided by the manufacturer).

The network manager should organize a regular field inspection every 6 to 12 months, depending on the instruments installed in the network, on the accessibility of the observing sites and on the maintenance organization.

Laboratory calibration: Those instruments that are at the end of their calibration interval, or show an uncertainty deviation beyond allowed limits during a field inspection, or instruments repaired by the maintenance service should return to a calibration laboratory prior to their re-use. Instruments should be calibrated in a conditioned environment (environmental chambers) by means of appropriate working standards and well defined procedures. These working standards should be compared and calibrated periodically with secondary standards and be traceable to international standards. Details on the strategy for traceability assurance are described in Volume I, Chapter 1, Annex 1.B.

1.7.3 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 instruments, 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 and Volume V, Chapter 5 of this guide).

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.

1.8 CONSIDERATION ABOUT SYSTEM SPECIFICATIONS AND COST

The installation of a new network of AWS or the transition from manual to automatic stations is a difficult matter and shall be managed as a project:

(a) A project team with the necessary management skills should be set up.

(b) Users' needs should be clearly established and translated into functional and technical specifications.

(c) Future processes of procurement, sites selection, initial installation and maintenance during the whole life time of the system have to be identified and documented.

(d) Explicit quality objectives should be defined:

  (i) Target uncertainty of measurement, understanding that it may be a compromise between state-of-the-art and the affordable costs, with associated calibration periodicity.

  (ii) Target siting classification for observing sites and accepted compromises in case of difficulties to find class 1 sites (see Volume I, Part 1, Annex 1.D).

  (iii) Target of the availability of data, both in real-time and delayed.

  (iv) Definition of an accepted service level (for example, maximum delay for fixing a problem on site).

  (v) Identification of the life duration of the network.

  (vi) Definition of the system redundancy (measurement, telecommunication, central unit system).

(e) The available telecommunication networks have to be identified and selected.

(f) Existing equipment to be reused or not, should be identified (instruments, central processing system, sites, site infrastructure, etc.).

(g) The procurement laws to follow, the initial budget and the running costs should be identified.

(h) The specifications for the full system should be written and the procurement procedure (tender, in-house development, external or internal installation and maintenance, etc.) should be selected.

(i) The procurement process, the acceptance tests for the first equipment, the acceptance tests for the serial equipment should be defined and executed.

(j) The first installations on site and the link to the central system (collecting platform, processing platform) should be validated.

(k) The stations and the central supervision tools and methods, with appropriate indicators, should be deploy.

(l) Regular site inspection should be planed.

(m) The reached performances should be measured, compared to the target and then corrective and preventive action should be taken, accordingly.

It must be understood that AWSs have many advantages, but do not eliminate the need of a well-established organization for using and maintaining them.

The cost of a network of AWSs is split between many parts and the cost of the AWS itself being a small percentage of the total costs which include:

(a) Cost of the observing site itself: piece of land, fence, and possible trench for mains power or telecommunication lines;

(b) Cost of the equipment: AWS, instruments, telecommunication modem or interface;

(c) Cost of the on-site installation and installing structures;

(d) Cost of the development and implementation of the central collecting and processing systems;

(e) The running expenditure for communications;

(f) The running cost for maintenance and calibration.

ANNEX. AUTOMATIC WEATHER STATIONS – LOW COST

1. INTRODUCTION

Historically the measurement of weather phenomena has been an activity performed by professional meteorological organisations, but in the last ten years, there has been a continually increasing number of lower cost automatic weather stations on the market (referred to as low-cost AWS). Low-cost AWS range in price from as low as $50 US up to typically $7000 US and come in a variety of designs and configurations.

There are some common features of low-cost AWS including:

(a) Relatively low cost;

(b) Low or very low power consumption;

(c) Transmission of data in real lime (with or without logging);

(d) Often small and compact.

There are three main classes of low-cost AWS: Compact; All in One; and Stand Alone Instruments (or IoT, Internet of Things).

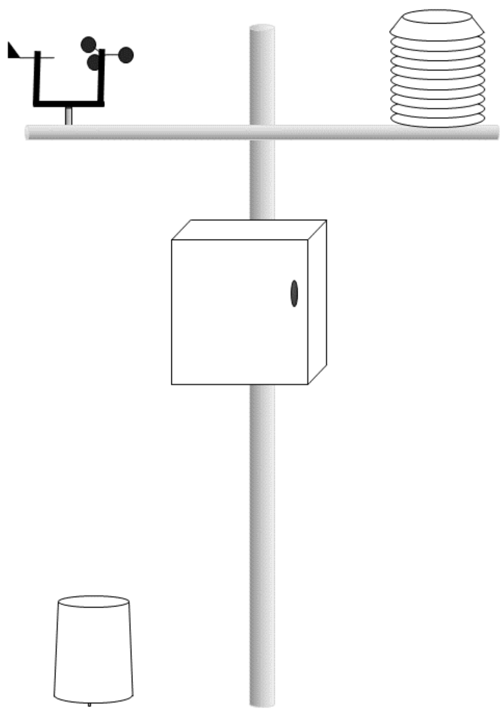

Figure 1. Example of a "Compact AWS"

"Compact AWS" consists of a mast, stand or pole with mounting arms for a variety of instruments and usually a cabinet to house a logger or processor, power supply and other modules (Figure 1). These AWSs are similar to professional metrological weather stations; they typically use individual instruments for each variable, and the instruments are capable of being calibrated. The instruments can also be adjusted and replaced individually. The AWS may have some data logging and data transmission capability with the flexibility to tailor the message communications to fit into an existing data reception system.

"All in One" generally refers to the instrument component of a low-cost AWS (Figure 1.). The most common configuration of an All in One AWS includes temperature, relative humidity and pressure instruments with the capacity to add instruments. Some also have one or more of: wind speed;

wind direction; precipitation; and solar radiation. There are also units that measure present weather variables such as hail and thunderstorms. Typically they are designed to be a single unit and mounted on a small post or mast. Some models include logging and battery storage that provide the entire system power supply, including transmission of limited volumes of data. However more commonly these are additional items and costs.

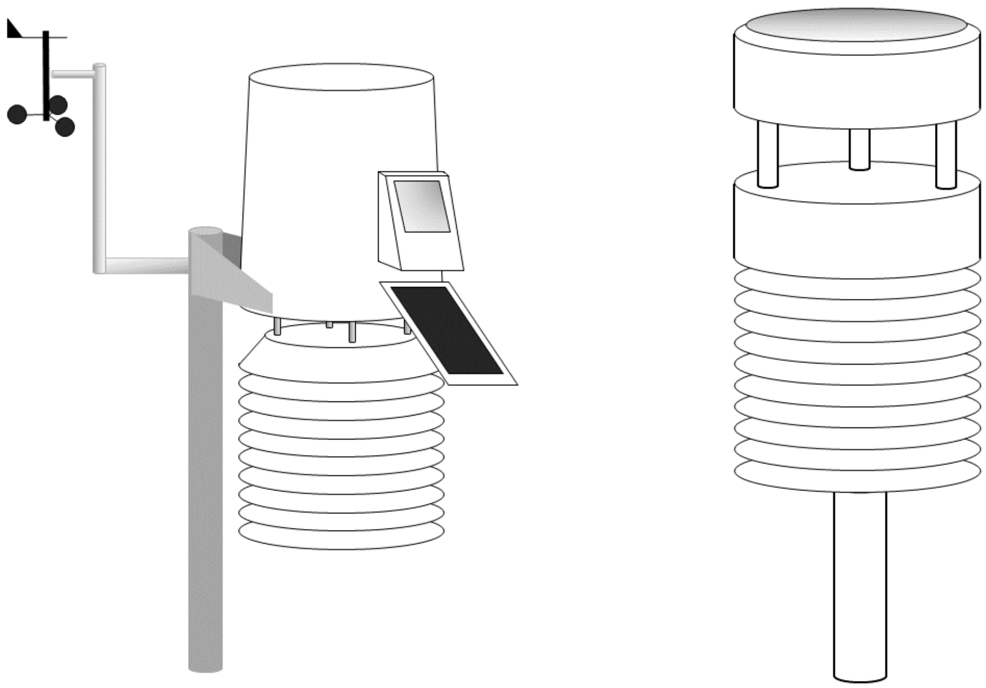

Figure 2 Examples of All in One style systems

"Stand Alone Instruments" are a rapidly emerging technology, and these are commonly referred to as the "Internet of Things" devices. These systems use a network of individual intelligent instruments, transmitting information using low-power and low bandwidth via Wi-Fi, Bluetooth or internet interfaces to centralised processing servers (WMO, 2012). There are also a growing number of add-ons to phones that measure weather parameters.

2. ADVANTAGES AND DISADVANTAGES

Depending on the intended use, each of these categories has its advantages and disadvantages.

“All in One” systems are simple to install and operate. However, the design tends to result in compromises in the quality of the information gathered. The instruments, all being in one small unit, means not all instruments can be exposed correctly, and some may compromise the measurements of others. Typically they also have small screens that can result in biased coupling of the instrument to the environment, for example significant increases in the observed temperature during the day and moderately decreases during the night. This biased coupling also results in significant spikes in temperature. “All in Ones” also have the disadvantage that when a single instrument fails, often the entire unit needs repair or replacement. Calibration of these units is difficult, and for some variables, this can only be performed by the manufacturer. Studies by KNMI (Vega, 2017) and Aston University (Bell et al., 2015) demonstrate that these instruments exhibit significant biases in their measurements. For example, the Aston University study showed hourly mean bias in the temperature of +0.7 °C in the summer and +0.4 °C in the winter. Additionally, the KNMI research demonstrated spikes of 1 to 2 °C in air temperature and gross underestimation of rainfall (62 % losses).

Robustness is also a consideration with these units. The units tend to be made of mass-produced plastic component that deteriorates with exposure to the elements. Their mounting systems also tend to be lightweight. As sold, the devices often include a rechargeable battery which is topped up by a small solar cell. Although this is adequate in warm climates, the battery often fails in sub-zero temperatures. Typically the devices do not include the facility for the use of an external power supply.

“Compact AWSs” have the advantage that they can use commercial off-the-shelf instruments, offering the capability to change out faulty instruments and allow for a better siting configuration. The masts and general infrastructure are lighter weight and less robust than professional weather stations and more likely to fail during severe weather events. An advantage of many of the “All in One” and “Compact AWSs“ is that they come with software for local data collection, distribution and display of data. Increasingly suppliers are providing cloud services where they collect and display data, and provide network statistics via a web browser interface and an API for interfacing to other data processing systems. This has the advantage that information is available from anywhere at any time and by many concurrent users. However, these software and data management systems reduce the users' options to expand networks. Most of these AWS systems will not interface to other makes of “Compact AWS” and “All in Ones”.

The Internet of Things (IoT) offers the ability to optimise the siting and choice of individual instruments. However, the operation and management of these networks can become complicated. This distributed technology is much newer and is not as proven as “Compact AWS” and “All in Ones”. Professional manufacturers of weather instruments have not started building instruments specifically for this market at this time. As a result, much of the available instruments are at the lower end of the market, produced by electronics integrators without extensive experience in the measurement of weather. Most of the devices the manufactured are consumer grade, meaning the ongoing quality of data very quickly becomes unknown.

3. SELECTION CONSIDERATIONS

When choosing a low-cost AWS there is a large range of issues to consider to ensure the system is "Fit for Purpose". One of the most significant considerations is defining the user requirements and then creating an appropriate specification for the AWS. Most manufacturers provide a specification for the sensor element, which relates to testing under laboratory conditions and without screens or other environmental interfaces. Additionally, there may be constraints on the way the instrument has been tested to achieve the specification. For example, the specification for relative humidity instruments is often for the instrument tested at a single temperature in the laboratory. It does not include considerations such as the effect of the full range of temperatures the instrument may experience in the field. Some may include testing over a range of temperatures, but not the full range of operational temperatures.

At the lower cost end, there may be no factory manufactured acceptance testing or calibration and adjustment, the manufacturer instead relying on design and development specifications to represent all manufactured units. All this means that when selecting an AWS, significant care needs to be taken to ensure specifications from different manufacturers are genuinely comparable. For example, if the specified measurement uncertainty is small compared to other manufacturers, it may mean it is only applicable over a narrower range of conditions. Alternately the specification may only be one standard deviation, not an uncertainty with a 95 % confidence interval.

When considering systems like an “All in One”, the specifications will not typically include the effect of enclosures such as the screen on the instrument in the field. They are unlikely to include the impact of effects such as turbulence on wind measurements or precipitation, nor the impact of the instrument not being mounted at a standard height.

In the case of an “All in One” system, purchasers should look for AWS with symmetrical design. This symmetry minimises the impact of turbulence and shadowing on instruments. Some systems have a significant amount of electronics which has the potential to affect temperature and humidity instrument readings. Consequently, it is advisable to choose instruments that have some separation between the electronics and the screen. Ideally, the screen should be at the bottom of the cylindrical system minimising heat transfer from other parts of the “All in One”.

The materials used to construct the system are also important. Metal screens can have a significant effect on the measured temperature (Warne, 1998) as can the size and colour of the screen. Screens significantly smaller than 200 mm in diameter and 250 mm height will result in poorer performance, exhibiting significant warming under insolation and some cooling overnight due to radiative cooling, compared to a standard siting (Warne, 1998). In general, the smaller the screen, the larger the impact. Even the colour of the screen, in the visible and infra-red spectrum, is important: where possible "white" should be used. Some manufacturers may provide a suitable screen but have large structures such as black or dark grey rain gauges, which act as a thermal mass and nearby radiation sources affecting other sensors (Bell et al., 2015).

4. OTHER MEANS OF LOWERING OPERATIONAL COST

The use of “Compact”, “All in One” or “Internet of Things” technologies as a means of obtaining low-cost observations is not necessarily straightforward. Depending on the quality of data required and the cost of human resources these solutions may not represent value for money. “All in One” AWS instruments are more inclined to drift and fail, and thus require more servicing. For countries where the workforce is the most significant expense, this can result in maintenance costs (including calibration) that outstrip the upfront savings in capital investment. If however, the intended use is to provide an increased density of observations in crowded environments, these systems may be the most economical solution. Using the manufacturers stated drift characteristics, these systems may need to be replaced three to seven times in a ten year period, and maintained or calibrated twice per year to keep them within their stated manufacturer's specification.

“Compact AWS” and “Internet of Things” systems that use high-quality instruments reduce the maintenance burden. However, if the value the systems provide is its contribution to recording extreme weather events, then the savings in infrastructure investment may be wasted if the system is lost or damaged during an extreme event. Currently, many of the IoT instruments are aimed at the amateur and home market, and as such are not suitable for use by NMHSs.

Low-cost AWS may have their place in a tiered network and can provide significant value if their performance and operating limitations are understood. Alternately, substantial operational costs can be saved on the operation of professional standard AWSs network by understanding the performance standards that the network achieves and the drivers of the cost to maintain the required standard. Substantial savings can be achieved through optimisation of network operations. Analysis of before-and-after calibration checks, failures of systems in the field, root-cause analysis, and effective asset management, provide the evidence needed to optimise the cost of operating a network. It is important for network managers to ask questions such as *“Are our systems being over or under-serviced?”; “Is the right preventative maintenance in place?”, “Are staff adequately trained?”, “Do we have the proper infrastructure in place for the environment in which the AWS is operating?”*. For countries where labour costs are high, then optimisation of maintenance can bring more significant savings than the reduction in the quality and robustness of capital investment. In countries where the capital cost of investment is high and labour costs are relatively low, then there should be careful consideration of what should be automated.

The reasons for introducing low-cost AWS into a professional meteorological network are varied. It may be to increase the density of observation points, create agility and flexibility with a network or to reduce the cost of operations. It is important to understand that just because these alternate systems have a lower upfront price tag, they may not be a "lower cost" solution in the longer term. Issues around user requirements for data availability and quality, cost of labour to maintain, operate and monitoring as well as the capital price of equipment need to be included in planning the overall network and its operation. Often the lower upfront price may be more costly.

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Chapter title in running head: CHAPTER 1. MEASUREMENTS AT AUTOMATIC WE…
Chapter_ID: 8_II_1_en
Part title in running head: PART II. OBSERVING SYSTEMS

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