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*a*~~1992).

~~At an AWS, the instrument measurements are read out or received by a central data-acquisition unit. The collected data from the autonomous measuring devices can be processed locally at the AWS or elsewhere, for example, at the central processor of the network (WMO, 2010*a*). Automatic weather stations may be designed as an integrated concept of various measuring devices in combination with the data-acquisition and processing units.~~ 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. ~~They achieve this~~ This is achieved by:

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

(b) Supplying, for manned stations, data ~~outside the normal working~~24 hours a day;

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

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

(e) Satisfying new observational needs and requirements;

(f) Reducing human errors;

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

(h) Measuring and reporting with high frequency 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 (~~2010*b*, 2011*c*~~2015a, 2015b).

~~Considering that AWSs are fully accepted as meteorological stations when providing data with accuracy comparable~~The performance of today's electronic is no longer a limitation factor to ~~that of conventional stations,~~achieve the accuracy requirements given in ~~Part~~Volume I, Chapter 1, Annex 1.A of ~~the~~this Guide ~~may also be applied, as appropriate,~~. The measurement uncertainties associated with an AWS are mainly linked to ~~AWSs~~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 ~~Part~~ Volume I and, in particular, with the chapters on quality management (Chapter 1), sampling (Chapter 2) and data reduction (Chapter 3) in ~~Part IV~~Volume V.

~~The~~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 ~~and to develop practical means of fulfilling them.~~for the planned system (WMO, 2017b).

~~Furthermore, it~~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 ~~always satisfactory~~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~~, by inference, to any Service~~ 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) Engage manufacturers in the system assessment and need for improvements in performance;~~

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

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

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

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

[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).

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 ~~subjective~~automated observations~~, and future changes in reporting code,~~ 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;

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

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

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

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

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

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

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

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

~~1.1.4 Climatological requirements~~[5]

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 ~~climate~~ datasets that the following areas be considered for action ~~(see WMO, 1993):~~[6]:

~~(a) In cases where an AWS replaces a manual observing system that has been in operation for a long time, a sufficient overlap in observation systems to facilitate maintaining the homogeneity of the historical record must be assured.~~~~[7]~~ (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 ~~climate~~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:

(~~i~~a) Wind speed and direction: 12 months

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

(~~iii~~c) Precipitation: 60 months

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

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

~~(b) Accurate metadata should be maintained for each AWS installation;~~~~[10]~~

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

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

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

~~[7] Note also WMO (2010*a*), section 3.2.1.4.4.4(c) "one year of parallel measurements does not suffice; preference is given to at least two years, depending on the climatic region".~~

[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".

~~[10] See Part I, Chapter 1, section 1.1.3.~~

~~(d) The existing and future requirements of climate data users should be defined precisely and considered in developing statements of requirement for automated observations by AWSs;~~[11]

~~(e) Climate users should be trained in the most effective use of AWS data;~~[12]

~~(f) Specifications for a standardized climatological AWS should be developed which would record a basic set of climate variables such as temperature, precipitation, pressure and wind. Standardized water vapour measurements should be included due to the significance of this parameter in climate-change studies. Extreme values of all variables should be accurately and consistently recorded in a way that can be precisely related to older, manually-observed, data.~~[13]

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. ~~It is possible to classify AWSs into a number of functional groups; these frequently overlap each other, however, and the classification then begins to break down. A general classification could include stations that provide data in real time and those that record data for non-real-time or off-line analysis. It is not unusual, however, for both of these functions to be discharged by the same AWS.~~

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

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

~~[11] See Part I, Chapter 1, Annex 1.E.~~

~~[12] For example, see WMO (1997), especially Part II – "Implementation and user training considerations".~~

~~[13] Ibid.~~

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

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

~~Since AWSs~~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~~ AWSs~~.

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 ~~its~~ 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 ~~should~~have to be ~~very well~~ coordinated.

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

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

~~An~~ 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 ~~consist of an integrated AWOS (~~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 ~~system) or a set of autonomous measuring devices connected to a data-collection and transmission~~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~~, preferably no smaller than 25 m x 25 m (Part~~ (see Volume I, Chapter 1, and WMO, ~~2010a~~2013), a series of automated ~~sensors~~instruments sited at the recommended positions and interconnected to one or more data collection units using interfaces, ~~or~~sited for ~~an AWOS, a set of sensors installed in close combination, but~~ not affecting each other~~, directly~~ and connected to a central processing unit (CPU) by means of shielded cables, fibre optics, or radio links;

(b) A CPU for ~~sensor~~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) ~~Peripheral equipment such as a~~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~~, a real-time clock, and built-in test equipment for automatic monitoring of the status of vital 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.

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

~~1.2.1 Sensors~~

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

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

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

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

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

~~Some specific considerations concerning AWS sensors are given in the following paragraphs. Achievable operational accuracies are given in Part I, Chapter 1, Annex 1.E[14] of the Guide. As~~

~~[14] As specified by the Meeting of Experts on Operational Accuracy Requirements (1991) and approved by the forty-fourth session of the Executive Council (1992) for inclusion in this Guide.~~

~~experimental results become available, these estimates will be updated by CIMO, as appropriate. Sensor (laboratory) calibration accuracy should be better by a factor of at least two allowing for transformation to linear response functions. Sensor resolution should be better by a factor of about three than the stated requirement (which includes the performance of the interface).~~

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

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

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

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

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

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

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

~~The problems associated with the short time-constant of many humidity sensors are more critical than for temperature sensors. As for temperature measurements, all types of sensors have to be~~

~~installed in proper radiation shields. Preference should be given to aspirated or well-ventilated radiation shields. Shields may be similar in construction to those used for temperature measurements. Large errors can occur due to aspiration and cleaning problems.~~

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

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

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

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

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

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

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

~~*Cloud height*: The measurement of cloud height at an AWS is now mostly accomplished with the aid of (laser) ceilometers. Reference is made to WMO (1988) for an evaluation of current systems. Difficulties are still experienced in processing automatically the signals from the sensors in order to produce accurate measurements of cloud-base height under the wide range of conditions encountered in nature, in particular rain and snow. Another difficulty is that the sensors sample~~

~~the cloud height only over a very small area of sky directly above the detector. When provided to a remote user, such information can present a dangerously incorrect picture of the state or coverage of the sky, especially if the data are to be used for aviation purposes. This may be overcome by the use of algorithms to estimate cloud cover during a 30 min processing interval. In some countries, the role of the ceilometer is, however, that of an aid to the observer who is watching the sky. Ceilometers normally require a significant amount of electrical power and cannot generally be used unless a conventional supply is available. Furthermore, their performance may be reduced or distorted by the accumulation of snow, dust or other forms of contamination on the window of the exit and front apertures of the optical or infrared beam.~~

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

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

~~1.2.2~~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~~ and on whether a unique hardware solution exists.~~. In general, the main functions of the CPU are data acquisition, data processing, data storage and data transmission.

In the majority of existing AWSs, all~~ of~~ these functions are carried out by one microprocessor-based system installed in a weather-proof enclosure as close to the instruments as possible~~ to the sensors~~, or at some local indoor location. If the unit is located near the ~~sensors~~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 ~~mains~~main power supply and operated as if it ~~were~~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~~ may also be executed by different units.~~. 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 ~~each~~ 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 ~~sensors~~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 ~~sensor~~instrument (for example, an intelligent ~~sensor~~instrument such as a laser ceilometer), a number of similar ~~sensors~~instruments (for example, thermometers), or a number of different ~~sensors~~instruments, such as analogue instruments connected to a data logger in the field.

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

~~*1.2.2.1 Data acquisition*~~

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 ~~sensor~~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. ~~*Signal conditioning*~~

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

~~*Sensor*~~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 ~~sensors~~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~~ for which a conductive material (at ground potential) is placed between~~

~~the signal cables and the interference source.~~. The additional use of a pair of wires that are entwined is effective in reducing electromagnetic coupling.

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

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

Digital isolation: Electrical modules are used to acquire digital input signals while breaking the galvanic connection between the signal source and the measuring equipment. The modules (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.

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

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

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

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

~~*Data-acquisition function*~~

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

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

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

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

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

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

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

1.~~2.2.2 Data processing~~

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

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

~~Existing AWOSs are equipped with 8-bit microprocessors and limited memory (32 to 64 kbytes). New systems using 16- or 32-bit microprocessors surrounded by a considerable amount of solid-state memory (up to 1 Mbyte) are becoming standard. These AWOSs provide more input/output facilities which operate at much higher processing speeds and are capable of performing complex computations. Together with new hardware, sophisticated software is applied which was, some years ago, available only in minicomputer systems. The unit can be equipped with different types of memories such as random access memories (RAM) for data and program storage, non-volatile programmable read-only memories (PROMs) for program storage (programs are entered by means of a PROM programmer), and non-volatile electrically erasable PROMs (EEPROMs) mostly~~

~~used for the storage of constants which can be modified directly by software. At most stations, the RAM memory is equipped with a battery backup to avoid loss of data during power failures. At non-real-time stations without data transmission facilities, data can be stored in external memories. Mechanical devices with tapes which were used for this purpose for many years are now replaced by memory cards (RAM with battery backup, EEPROMs, etc.), which have a much higher reliability.~~

~~1.2.2.~~3 ~~Data transmission~~

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

~~1.2.3 Peripheral equipment~~

.4 Power supply~~:~~

The design and capability of an AWS depend critically ~~upon~~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~~ in motor vehicles~~, consideration should be given to the use of 12 V direct current power supply. Where mains power is available, the~~ 12 V~~ batteries could be float-charged from the main supply. Such a system provides the advantage of automatic backup power in the event of a mains power failure. 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 ~~upon~~on batteries ~~that may, or may not, be charged~~nearly always sourced by ~~an auxiliary~~solar cells or other power ~~source~~sources, such as a diesel generator~~,~~ and wind- or water-driven generator~~, or solar cells.~~. However, such low-power systems cannot, in general, support the more complex ~~sensors~~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~~, raingauges~~ 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, ~~of~~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.

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

~~*Built-in test equipment*: Vital parts of an AWS often include components whose faulty operation or failure would seriously degrade or render useless the principal output. The inclusion of circuits to monitor automatically these components' status is an effective means of continuously controlling their performance during operation. Examples are: a power-failure detector which restarts the processor and continues the AWS function after a power failure; a "watchdog" timer to monitor~~

~~the proper operation of microprocessors; and test circuits for monitoring the operation of station subsystems such as battery voltage and charger operation, aspirators (temperature and humidity screens), A/D converters, heaters, etc. Status information can be automatically displayed on site or input into the CPU for quality-control and maintenance purposes.~~

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

~~1.3~~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

~~When designing or specifying an~~ The three main designs of AWS ~~it is a guiding principle that the cost of developing and testing~~have different frameworks for the software ~~will be one of the largest financial elements in the package.~~:

(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 ~~exercised~~taken in the preliminary design and strong discipline maintained while coding, complex software readily ~~become~~becomes inflexible and difficult to maintain. Minor changes to the requirements~~—~~, such as those often induced by the need for a new ~~sensor~~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 ~~microprocessor~~hardware configuration and comprising all software to develop and run application programs.

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

1.~~3~~4.1 ~~System software~~Operating system

~~The software for many existing AWSs is developed by the manufacturer in accordance with user requirements and is put into the CPU memory in a non-readable format for the user~~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, ~~depends~~ entirely depends on the manufacturer in the event of malfunctions or modifications.

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

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

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.~~3~~4.2 Application software

The processing functions that must be carried out ~~either~~ by the CPU, the ~~sensor~~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, ~~however,~~ some or all of the following operations are required: initialization, sampling of ~~sensor~~instrument output, conversion of ~~sensor~~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. ~~The order in which these functions are arranged is only approximately sequential.~~ Quality~~-~~control may be performed at different levels: immediately after sampling, after deriving meteorological variables, ~~or~~ after the manual entry of data and message formatting~~.~~, or in the central system (quality control is often split between the AWS itself and the central system). If there are no ~~checks on~~ data quality~~-~~ control and message content checks, the AWS data are likely to contain undetected errors. While linearization may be inherent in the ~~sensor~~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.~~3~~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 ~~first~~ requires first a number of specific parameters, such as~~, among others,~~ those that are related to the station (station code (ID) number, altitude, latitude and longitude~~);~~), date and time~~;~~, physical location of the ~~sensor~~instrument in the data-acquisition section~~;~~, and type and characteristics of ~~sensor~~instrument-conditioning modules~~; conversion~~. Conversion and linearization constants for ~~sensor~~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 ~~latest~~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.~~3~~4.2.2 Sampling and filtering

Sampling ~~can be defined as~~is the process of obtaining a ~~well-spaced~~discrete sequence of measurements of a ~~variable~~quantity. To digitally process meteorological ~~sensor~~instrument signals, the question arises of how often the ~~sensor~~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. ~~A generally~~Generally accepted rule of thumb is to sample at least once during the time constant of the ~~sensor~~instrument. However, as some meteorological variables have high frequency components, proper filtering or smoothing should be accomplished first, by selecting ~~sensors~~instruments with a suitable time-constant or by filtering and smoothing techniques in the signal-conditioning modules ~~(see Part IV~~. More details are presented in Volume V, Chapter 2~~)~~.

~~Considering the need for the interchangeability of sensors and homogeneity of observed data, it is recommended:~~[15]

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

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

~~(ii) Do not exceed~~atmosphere, the ~~time constant~~introduction of ~~an analogue low-pass filter following~~noise into the ~~linearized output~~measurement process by electronic devices and, in particular the use of ~~a fast response sensor; or~~

~~(iii) Are sufficient in number to ensure that~~ instruments with short time-constants make averaging a most desirable process for reducing the uncertainty of ~~the average of the samples is reduced to an acceptable level, for example, smaller than the required accuracy of the average;~~reported data.

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

~~1.3~~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 ~~sensor~~instrument data consists of the transformation of the electrical output values of ~~sensors~~instruments or signal-conditioning modules into meteorological units. The process involves the application of conversion algorithms ~~making use of~~sometimes using constants and relations obtained during calibration procedures.

An important consideration is that some ~~sensors~~instruments are inherently non-linear, namely their outputs are not directly proportional to the measured atmospheric variables (for example, a resistance thermometer~~), that some~~). Other measurements are influenced by external variables in a non-linear ~~relation~~relationship (for example, some pressure and humidity ~~sensors~~instruments

~~[15] Recommended by the Commission for Instruments and Methods of Observation at its tenth session (1989) through Recommendation 3 (CIMO-X).~~

are influenced by the temperature~~) and that, although the sensor itself~~). 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 ~~output~~proper variable to be averaged in order to produce estimates of ~~a rotating beam ceilometer with photo detector and shaft-angle encoder providing backscattered light intensity as a function of angle is nonlinear in cloud height). As a consequence~~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 ~~sensor~~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 ~~only~~ average only linear variables. More details are presented in Volume V, Chapter 3.

~~*1.3.2.4 Instantaneous meteorological values*~~

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

~~In order to standardize averaging algorithms it is recommended:~~[16]

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

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

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

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

~~1.3.2.5~~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

~~[16] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 6 (CIMO-IX).~~

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 ~~sensors~~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.~~3~~4.2.~~6~~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. ~~Examples of~~For example, data reduction ~~are~~is the calculation of ~~dewpoint~~dew point temperature ~~values~~ from the original relative humidity and air temperature measurements, and the reduction of pressure to mean sea level. Statistical data include data extremes over one or more time periods (for example, temperature), total amounts ~~(for example, rain)~~ 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 ~~an AWS~~ the AWS's level, or ~~at~~in a central ~~network~~ processing ~~system where more~~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 ~~power is normally available.~~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 ~~an extensive~~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.

~~Formal recommendations exist for the computation of pressure tendency[17] and humidity quantities[18] (Part I, Chapter 4, Annex 4.B).~~

~~[17] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 7 (CIMO-IX).~~

~~[18] Recommended by the Commission for Instruments and Methods of Observation at its tenth session (1989) through Recommendation 7 (CIMO-X).~~

~~WMO investigated the methods for pressure reduction used by Members in 1952 (WMO, 1954) and concluded that the "international formula" (using the formula of Laplace or Angot's tables) or some "simplified" methods are in practice (for example, for "low-level" stations[19], see, Part I, Chapter 3). As a result of this inquiry, a study of the standardization of methods of reduction was undertaken and one general equation of pressure reduction was recommended as standard[20] (WMO, 1964). Nevertheless, this recommended method, the "international formula" and methods using simplified formulae are still in common practice (WMO, 1968).~~

~~*1.3*~~*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 (~~2011*b*). Depending on the type of message and the elements to be coded, the messages can be generated fully or semi-automatically. Generating fully automatic messages implies that all elements to be coded are measurable data, while generating semi-automatic messages involves the intervention of an observer for entering visual or objective observations, such as present and past weather, the state of the ground, and cloud type. Message coding algorithms should not be underestimated and require considerable~~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. ~~They also occupy a considerable amount of memory that can be critical for small performance stations. It should be noted that observational data could be transmitted to the central network processing system,~~

~~[19] Recommended by the Commission for Instruments and Methods of Observation at its first session (1953) through Recommendation 13 (CIMO-I) and adopted by EC-IV.~~

~~[20] Based on the recommendations by the CIMO-I Working Committee II on "Reduction of Pressure" (WMO, 1954, Part 2).~~

~~where more computer power is normally available for message coding.~~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.~~3.2.8~~5 QUALITY CONTROL

The purpose of quality~~-~~ control at an AWS is to minimize automatically the number of inaccurate ~~observations~~measurement data and the number of missing ~~observations~~data by using appropriate hardware and software routines. Both purposes are served by ensuring that each ~~observation is computed~~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~~ and~~, while the computation can still proceed, ~~uncontaminated~~not being contaminated by that sample.

Quality~~-~~ control ~~achieves assured~~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. ~~Currently, there is no agreed set of procedures or standards for the various AWS platforms. Such a set of procedures should be developed and documented.~~

In modern AWSs, the results of data quality-control procedures ~~for sensors~~applied to instruments which reveal the reasons why a measurement is ~~suspect~~suspicious or erroneous~~,~~ and ~~the results~~ of hardware self-checks by built-in test equipment~~,~~ are stored in appropriate housekeeping buffers. ~~The~~ The transmission of these results and the visual display of these status indicators ~~forms~~form a very handy tool for continuous monitoring of the network, and during field or remote maintenance. The transmission of housekeeping buffers~~ — either~~, 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 ~~a valuable possible approach~~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 ~~Part IV~~Appendix VI.2 of the Guide to the Global Observing System (WMO 2013) and in Volume V, Chapter 1~~, and as basic quality-control procedures in WMO (1993).~~ of this Guide. The following is a ~~practical elaboration~~brief summary of the ~~recommendations.~~guidelines available in WMO (2013).

Intra-~~sensor~~instrument checks

~~Intra-sensor checks~~~~: This is when each sensor~~: Each instrument sample is checked at the earliest practical point in the processing, taking into account ~~sensor~~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: ~~This is a~~A gross check that the measured value lies within the absolute limits of variability. These limits are related to the nature of the meteorological variable or phenomena, but depend also on the measuring range of selected ~~sensors~~instruments and data-acquisition hardware. Additional checks against limits which are functions of geographical area, season and time of year could be applied. ~~Suggested limits for these additional checks are presented in Tables 6.3–6.9 in Chapter 6 of WMO (1993). The checks provide information as to whether the values are erroneous or suspect~~The checks help identifying erroneous or suspicious values.

Plausible rate of change: ~~This checks~~Checks for a plausible rate of change from a preceding acceptable level. ~~The effectiveness of the check~~The test settings depend on the observed parameter and the atmospheric phenomena which could influence it. It also depends ~~upon the temporal consistency or persistence of~~ 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 ~~and is best applied~~is an indication for malfunctioning (for example, a cup and vane anemometer starting to ~~data~~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 ~~high temporal resolution (high sampling rate) as the correlation between adjacent~~valid samples ~~increases with the sampling rate. One obvious difficulty is determining how quickly an atmospheric variable can change taking into account the response characteristics~~*in a period*: This determines the validity of the ~~sensor in question. Additional time consistency checks using comparisons of data between two consecutive reports can be made. WMO (1993) provides checking tolerances for different time periods on the synoptic scales (1, 2, 3, 6, 12 h) for air temperature, dewpoint, and pressure tendency~~average and its suitability for use in further calculations.

Inter-~~sensor~~instrument checks

: It is possible to make internal consistency checks of a measured variable against other measured variables, based ~~upon~~on established physical and meteorological principles~~. Some examples are as follows: dewpoint~~, 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 ~~sensor problem; and zero average wind speed and non-zero wind direction (variance) suggest a defective wind-speed sensor~~instrument.

~~*Observations entered manually*~~

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

~~*Hardware checks*~~

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

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 ~~Global Telecommunication System~~GTS, it is of vital importance ~~that~~to execute all the above checks ~~are executed~~ very carefully. In addition, compliance with regulations concerning character, number, format, and so forth, should be controlled. Proper actions are to be considered ~~in cases of~~when values ~~that~~ are classified as ~~suspect~~suspicious.

~~***1.3.2.9 Data storage***~~

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

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

~~***1.3.2.10 Data transmission***~~

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

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

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

~~(c) In AWS emergency conditions when certain meteorological thresholds~~, the quality control checks are ~~crossed.~~

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

~~One-way communications~~

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

~~Two-way communications~~

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

~~AWS network communication~~

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

~~Integrated services digital network~~

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

~~*Wide area network communications*~~

~~With the worldwide increase in data traffic and the use of modern communications protocols, together with the increased computing and data-storage capability at remote terminals, it is now common to view the remote AWS and the central control and data-acquisition computer as nodes of a wide area network (WAN). The data or control message is divided into "packets" according to rules (protocols) such as X.25 or the faster frame relay. Each data packet is routed through the telecommunication provider's switched data network and may arrive at the destination by different routes (making efficient use of the network with other unrelated packets). At the destination, the packets are reassembled under the protocol after variable delays to reform the message. Error detection with the automatic resending of corrupted or lost packets ensures reliable transmission. Note the contrast with ordinary PSTN based on circuit-switching technology, in which a dedicated line is allocated for transmission between two parties. Circuit-switching is ideal when real-time data (like live audio and video) must be~~ . If the raw data samples are not transmitted ~~quickly and arrive in the same order in which it was sent. Packet switching is more efficient and robust for data that can withstand some short delay in transmission. Message costs are related to connect time and data volume. There should be a means to terminate the connection reliably when data collection is finished, as a faulty AWS may keep the line open and incur unwanted costs.~~

~~Frame relay and asynchronous transfer mode~~

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

~~Transmission protocol~~

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

~~Switched or dedicated circuits~~

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

~~1.3.2.11 Maintenance and calibration~~

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

~~*1.3.2.12 Data display*~~

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

~~1.4~~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 ~~Part~~Volume I, Chapter 1, Annex 1.D, as well as in WMO (~~2010*a*, 2010*b*~~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~~, of course,~~ be able to withstand severe meteorological conditions. The cost of providing systems capable of operating under all foreseen circumstances ~~at an automatic station~~ is high and may be prohibitive~~; it~~. It is essential ~~that, before specifying or designing an AWS,~~to obtain a thorough understanding of the working environment anticipated for the AWS~~ be obtained~~, 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.~~5~~ ~~CENTRAL NETWORK DATA PROCESSING~~

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

~~1.5.1 Composition~~

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

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

~~1.5.2 Quality management of network data~~

~~This topic is discussed further in Part IV, Chapter 1. It is recommended that operators of networks:~~[21]

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

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

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

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

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

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

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

~~Monitoring algorithms, by which reported values are regularly tested in space and time against an analysed numerical field, are very powerful ways to identify errors and to establish the need for investigative or remedial action. The low level of turbulent fluctuations in atmospheric pressure and the confidence with which local geographic influences can be removed by normalizing all observations to a common reference level make atmospheric pressure a prime candidate for this~~

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

~~type of quality control. By averaging over space or time, observations with other variables should be susceptible to this analysis as well. However, local orographic effects must be carefully considered and taken into account.~~

~~1.6~~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. ~~In view of~~With the increasing reliability of the electronic components of an AWS, preventive maintenance, including services and ~~sensor~~instrument calibration, ~~will become~~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~~. Indeed,~~ of operation. Repairing costs ~~for repair~~ and costs of different components often rapidly increase ~~quite rapidly~~ after a system is no longer in active distribution, thus making ~~it~~ necessary to replace modules by new ones with different technology, ~~as~~because exact replacements are seldom found~~. Examples include~~, for example, transferring ~~data from one recording medium to another and~~ programs and operating systems from one processor to another, introducing modular changes for system reliability, connecting with new telecommunication systems, and so ~~on~~forth. In order to reduce the costs for this ~~kind~~type of maintenance, it is desirable ~~that~~to establish widely accepted standards on equipment and interfaces, as well as on software, ~~be established~~ and ~~included~~include them in AWS technical specifications.

~~Since the maintenance~~The installation of a network of automatic stations ~~is often~~must not be seen as a ~~grossly underestimated task, it~~one shot investment. It is essential to organize maintenance according to a rational plan that details all the functions and arranges them ~~so as~~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 ~~sensors~~instruments or other modules in the field because conditions ~~do~~might not favour effective work. ~~Also, because of high staff costs and relatively low equipment costs, it is more cost-effective to discard faulty modules rather than to repair them.~~ It is recommended that corrective maintenance in the field ~~be~~is carried out by specialized technical personnel from a regional or national centre, depending on the size of the country~~, and to leave simple~~. Simple preventive or corrective maintenance ~~to the~~can be done by a local observer (when available~~).~~) or a local design operator. The ~~periodic~~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 ~~sensors~~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 ~~sensors~~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 ~~should be~~are capable of detecting and eliminating complex problems in ~~sensors~~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 ~~desirable~~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.

~~The scheme outlined above is suitable for big countries.~~ For small countries, the tasks of the regional centres could be taken over by the national centre. Developing countries could consider establishing joint maintenance arrangements with neighbouring ~~counties~~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 ~~support~~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 ~~Part IV~~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

~~Sensors~~Instruments, in particular AWS ~~sensors~~instruments with electrical outputs, ~~show accuracy~~ drifts in time and, consequently, ~~need~~ regular inspection and calibration are needed. In principle, the calibration interval is determined by the drift specifications given by the manufacturer and the required ~~accuracy~~uncertainty. WMO international instrument intercomparisons also provide some objective indications of ~~sensor accuracy~~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. ~~Refer to the different chapters of Part I and to Part IV, Chapter 4, for~~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: ~~It is easy to overlook the requirement that appropriate~~Appropriate calibration facilities and instrumentation should be available prior to the procurement and installation of AWSs, in order to ~~be able to verify~~enable verification of the specifications given by the manufacturer, ~~to test~~testing the overall performance of the station and ~~to verify that~~inspection if transportation ~~did not affect~~has affected the measuring characteristics of the equipment.

Field inspection: The periodic replacement or comparison of AWS ~~sensors~~instruments with travelling standards at the station is an absolute requirement to monitor the performance of the ~~sensors~~instruments. Travelling standards having similar filtering characteristics to the AWS measuring chain and with a digital read-out are ~~to be~~ preferred. In many countries, two travelling standards of the same type are used to prevent possible problems with change of accuracy ~~change problems~~ due to transportation. In order to be able to detect small drifts, the travelling standards should have an ~~accuracy~~uncertainty that is much ~~better~~lower than the relevant station ~~sensor~~instrument and should be installed during the comparison process in the same environmental conditions as the ~~sensors~~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 ~~when accuracy~~, 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: ~~Instruments~~Those instruments that are at the end of their calibration interval, ~~instruments showing~~or show an ~~accuracy~~uncertainty deviation beyond allowed limits during a field inspection~~ and~~, or instruments repaired by the maintenance service should return to a calibration laboratory prior to their re-use. ~~Sensors~~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.

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

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

1.~~8~~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 ~~sensors~~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.

~~SECTION: Chapter_book~~

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).

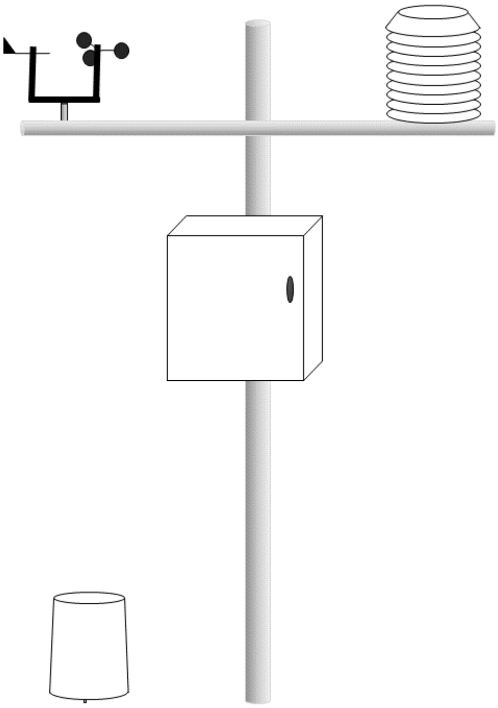

Figure 1. Example of a "Compact AWS"

"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.

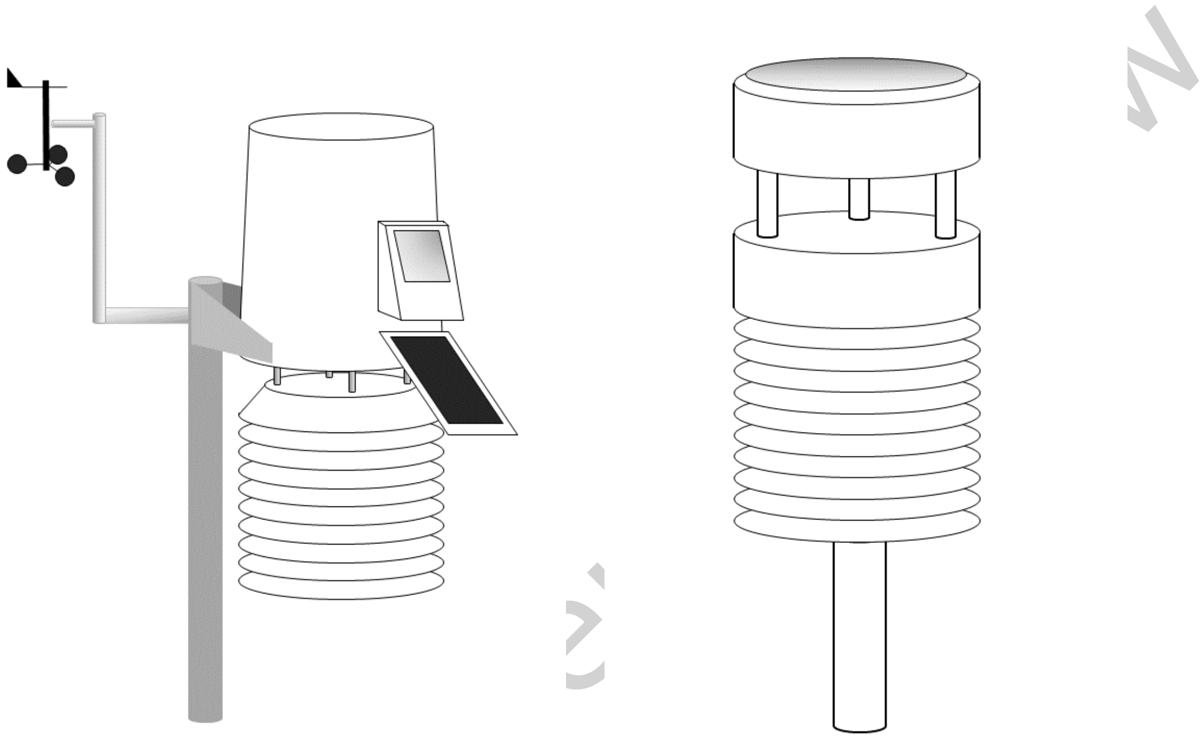

Figure 2 Examples of All in One style systems

"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.

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

REFERENCES AND FURTHER READING

Bell S., D. Cornford and L. Bastin, 2015: How good are citizen weather stations? Addressing a biased opinion. *Weather*, 70(3):75-84.

United Nations Environment Programme, 2017: Minamata Convention on Mercury http://www.mercuryconvention.org/Portals/11/documents/Booklets/COP1%20version/Minamata-Convention-booklet-eng-full.pdf.

Vega, S., 2017: *The quality of low-cost weather stations*. Report by KNMI and The Hague University of Applied Sciences.

Warne, J., 1998: *A Preliminary Investigation of Temperature Screen Design and Their Impacts on Temperature Measurements.* Instrument Test Report 649. Bureau of Meteorology, Melbourne.

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

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

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

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

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

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

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

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

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

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

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

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

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

———, 1995: Papers presented at the International Workshop on Experiences with Automatic Weather Stations on Operational Use Within National Weather Services (WMO/TD-No. 670)

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

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

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

———, ~~2010a:~~2010 (Updated in 2017): *Guide to the Global Observing System* (WMO-No. 488). Geneva~~.~~

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

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

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

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

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

———, 2015a (Updated in 2017): *Technical Regulations* (WMO-No. 49), Volume I. Geneva.

———, 2015b (Updated in 2017): *Manual on the WMO Integrated Global Observing System* (WMO-No. 1160). Geneva.

———, 2016: *Manual on Codes* (WMO-No. 306), Volumes I.1 and I.2. Geneva.

———, 2017a: WMO International Conference on Automatic Weather Stations (ICAWS-2017), "Automatic Weather Stations for environmental intelligence – the AWS in the 21st century" (WMO-IOM report No. 127)

———, 2017b: *WMO Observing Systems Capability Analysis and Review Tool* (WMO OSCAR) https://www.wmo-sat.info/oscar/

———, 2017c: *Desktop analysis of commercially available "All in One" and "Compact" weather stations- How well can we do it?* (J. Warne). *Papers Presented at the WMO International Conference on Automatic Weather Stations (ICAWS-2017)*. Instruments and Observing Methods Report No. 127. Geneva.