PART III

QUALITY ASSURANCE AND MANAGEMENT OF OBSERVING SYSTEMS

PART III. QUALITY ASSURANCE AND MANAGEMENT OF OBSERVING SYSTEMS

CONTENTS

Page

Page

CHAPTER 1

QUALITY MANAGEMENT

1.1 GENERAL

This chapter is general and covers operational meteorological observing systems of any size or nature. Although the guidance it gives on quality management is expressed in terms that apply to large networks of observing stations, it should be read to apply even to a single station.

Quality management

Quality management provides the principles and the methodological frame for operations, and coordinates activities to manage and control an organization with regard to quality. Quality assurance and quality control are the parts of any successful quality management system. Quality assurance focuses on providing confidence that quality requirements will be fulfilled and includes all the planned and systematic activities implemented in a quality system so that quality requirements for a product or service will be fulfilled. Quality control is associated with those components used to ensure that the quality requirements are fulfilled and includes all the operational techniques and activities used to fulfil quality requirements. This chapter concerns quality management associated with quality control and quality assurance and the formal accreditation of the laboratory activities, especially from the point of view of meteorological observations of weather and atmospheric variables.

The ISO 9000 family of standards is discussed to assist understanding in the course of action during the introduction of a quality management system in a National Meteorological and Hydrological Service (NMHS); this set of standards and contains the minimum processes that must be introduced in a quality management system for fulfilling the requirements of the ISO 9001 standard. The total quality management concept according to the ISO 9004 guidelines is then discussed, highlighting the views of users and interested parties. The ISO/IEC 17025 standard is introduced. The benefits to NMHSs and the Regional Instrument Centres (RICs) from accreditation through ISO/IEC 17025 are outlined along with a requirement for an accreditation process. The ISO/IEC 20000 standard for information technology (IT) service management is introduced into the discussion, given that every observing system incorporates IT components.

Quality assurance and quality control

Data are of good quality when they satisfy stated and implied needs. Elsewhere in this Guide explicit or implied statements are given of required accuracy, uncertainty, resolution and representativeness, mainly for the synoptic applications of meteorological data, but similar requirements can be stated for other applications. It must be supposed that minimum total cost is also an implied or explicit requirement for any application. The purpose of quality management is to ensure that data meet requirements (for uncertainty, resolution, continuity, homogeneity, representativeness, timeliness, format, and so on) for the intended application, at a minimum practicable cost. All measured data are imperfect, but, if their quality is known and demonstrable, they can be used appropriately.

The provision of good quality meteorological data is not a simple matter and is impossible without a quality management system. The best quality systems operate continuously at all points in the whole observing system, from network planning and training, through installation and station operations to data transmission and archiving, and they include feedback and follow-up provisions on timescales from near-real time to annual reviews and end-to-end process. The amount of resources required for an effective quality management system is a proportion of the cost of operating an observing system or network and is typically a few per cent of the overall cost. Without this expenditure, the data must be regarded as being of unknown quality, and their usefulness is diminished.

An effective quality system is one that manages the linkages between preparation for data collection, data collection, data assurance and distribution to users to ensure that the user receives the required quantity. For many meteorological quantities, there are a number of these preparation-collection-assurance cycles between the field and the ultimate distribution to the user. It is essential that all these cycles are identified and the potential for divergence from the required quantity minimized. Many of these cycles will be so closely linked that they may be perceived as one cycle. Most problems occur when there are a number of cycles and they are treated as independent of one another.

Once a datum from a measurement process is obtained, it remains the datum of the measurement process. Other subsequent processes may verify its worth as the quantity required, use the datum in an adjustment process to create the quality required, or reject the datum. However, none of these subsequent processes changes the datum from the measurement process. Quality control is the process by which an effort is made to ensure that the processes leading up to the datum being distributed are correct, and to minimize the potential for rejection or adjustment of the resultant datum.

Quality control includes explicit control of the factors that directly affect the data collected and processed before distribution to users. For observations or measurements, this includes equipment, exposure, measurement procedures, maintenance, inspection, calibration, algorithm development, redundancy of measurements, applied research and training. In a data transmission sense, quality control is the process established to ensure that for data that is subsequently transmitted or forwarded to a user database, protocols are set up to ensure that only acceptable data are collected by the user.

Quality assurance is the best-known component of quality management systems, and it is the irreducible minimum of any system. It consists of all the processes that are put in place to generate confidence and ensure that the data produced will have the required quality and also include the examination of data at stations and at data centres to verify that the data are consistent with the quality system goals, and to detect errors so that the data may be either flagged as unreliable, corrected or, in the case of gross errors, deleted. A quality system should include procedures for feeding back into the measurement and quality control process to prevent the errors from recurring. Quality assurance can be applied in real-time post measurement, and can feed into the quality control process for the next process of a quality system, but in general it tends to operate in non-real time.

Real-time quality assurance is usually performed at the station and at meteorological analysis centres. Delayed quality assurance may be performed at analysis centres for the compilation of a refined database, and at climate centres or databanks for archiving. In all cases, the results should be returned to the observation managers for follow-up.

A common component of quality assurance is quality monitoring or performance monitoring, a non-real-time activity in which the performance of the network or observing system is examined for trends and systematic deficiencies. It is typically performed by the office that manages and takes responsibility for the network or system, and which can prescribe changes to equipment or procedures. These are usually the responsibility of the network manager, in collaboration with other specialists, where appropriate.

Modern approaches to data quality emphasize the advantages of a comprehensive system for quality assurance, in which procedures are laid down for continuous interaction between all parties involved in the observing system, including top management and others such as designers and trainers who may otherwise have been regarded as peripheral to operational quality concerns after data collection. The formal procedures prescribed by the International Organization for Standardization (ISO) for quality management and quality assurance, and other detailed procedures used in manufacturing and commerce, are also appropriate for meteorological data.

1.2 THE ISO 9000 FAMILY, ISO/IEC 17025, ISO/IEC 20000 AND THE WMO QUALITY MANAGEMENT FRAMEWORK

The chapter gives an explanation of the related ISO standards and how they inerconnect.

Proficiency in ISO quality systems is available through certification or accreditation, and usually requires external auditing of the implemented quality system. Certification implies that the framework and procedures used in the organization are in place and used as stated. Accreditation implies that the framework and procedures used in the organization are in place, used as stated and technically able to achieve the required result. The assessment of technical competence is a mandatory requirement of accreditation, but not of certification. The ISO 9001 is a standard by which certification can be achieved by an organization, while accreditation against the ISO/IEC 17025 is commonly required for laboratories and routine observations.

The ISO 9000 standard has been developed to assist organizations of all types and sizes to implement and operate quality management systems. The ISO 9000 standard describes the fundamentals of quality management systems and gives definitions of the related terms (for example, requirement, customer satisfaction). The main concept is illustrated in Figure 1.1. The ISO 9001 standard specifies the requirements for a quality management system that can be certified in accordance with this standard. The ISO 9004 standard gives guidelines for continual improvement of the quality management system to achieve a total quality management system. The The ISO 19011 standard provides the guidance on auditing the quality management system. All these standards are described in more detail in the related documents of the WMO Quality Management Framework.

1.2.1 ISO 9000: Quality management systems – Fundamentals and vocabulary

The following eight quality management principles are the implicit basis for the successful leadership of NMHSs of all sizes and for continual performance improvement:

(a) Customer focus;
(b) Leadership;
(c) Involvement of people;
(d) Process approach;
(e) System approach to management;
(f) Continual improvement;
(g) Factual approach to decision-making;
(h) Mutually beneficial supplier relationships.

All these principles must be documented and put to practice to meet the requirements of the ISO 9000 and 9001 standards to achieve certification. The main topic of these standards is the process approach, which can simply be described as activities that use resources to transform inputs into outputs.

The process-based quality management system is simply modelled in Figure 1.2. The basic idea is that of the mechanism likely to obtain continual improvement of the system and customer satisfaction through measuring the process indices (for example, computing time of a GME model, customer satisfaction, reaction time, and so forth), assessing the results, making management decisions for better resource management and obtaining inevitably better products.

1.2.2 ISO 9001: Quality management systems – Requirements

The basic requirements for a quality management system are given by this standard, including processes for improvement and complaint management and carrying out management reviews. These processes are normally incorporated in the quality manual. The ISO 9001 standard focuses on management responsibility rather than technical activities.

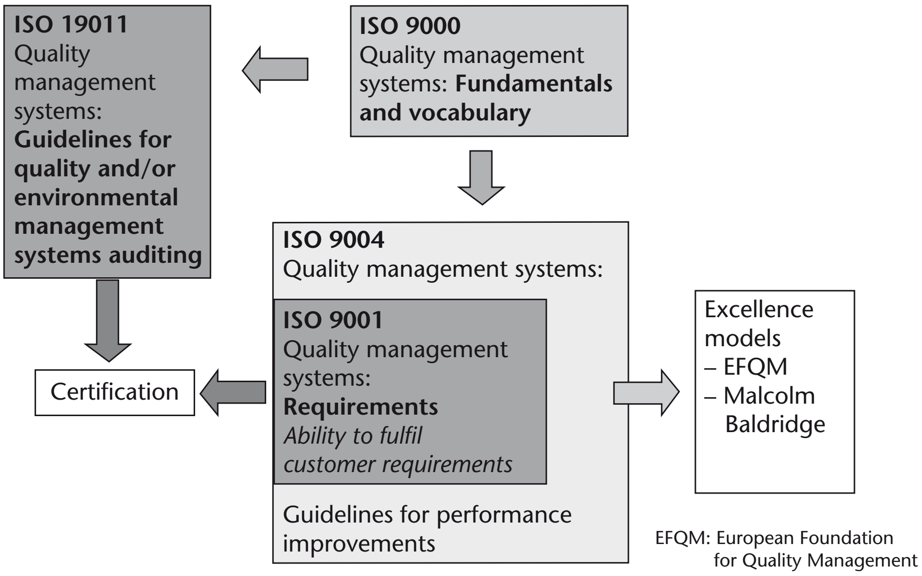
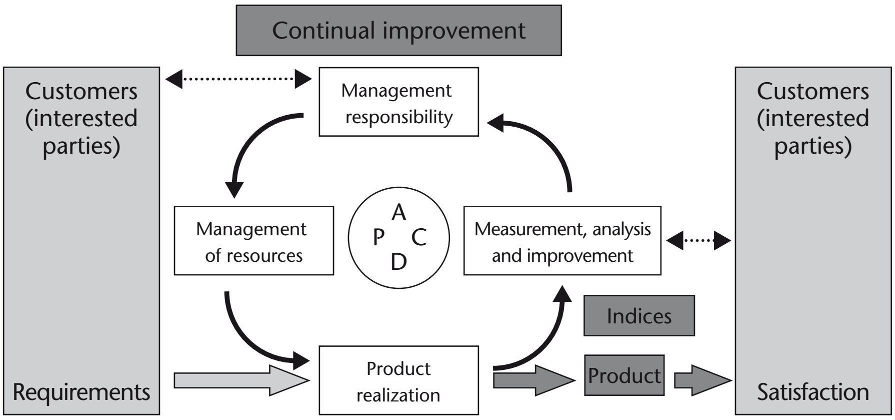


Figure 1.1. The main concept of the ISO 9000 standards and the dependencies



P = Plan, D = Do, C = Check, A = Act

Figure 1.2. The PDCA control circuit (also named the Deming-circuit)

To achieve certification in ISO 9001, six processes must be defined and documented by the organization (NMHS), as follows:
(a) Control of documents;
(b) Control of records;
(c) Control of non-conforming products;
(d) Corrective action;
(e) Preventive action;
(f) Internal audit.

Furthermore, there must be a quality manual which states the policy (for example, the goal is to achieve regional leadership in weather forecasting) and the objectives of the organization (for example, improved weather forecasting: reduce false warning probability) and describes the process frameworks and their interaction. There must be statements for the following:
(a) Management;
(b) Internal communication;
(c) Continual improvement;
(d) System control (for example, through management reviews).

Exclusions can be made, for example, for development (if there are no development activities in the organization).

The documentation pyramid of the quality management system is shown in Figure 1.3. The process descriptions indicate the real activities in the organization, such as the data-acquisition process in the weather and climate observational networks. They provide information on the different process steps and the organizational units carrying out the steps, for cooperation and information sharing purposes. The documentation must differentiate between periodic and non-periodic processes. Examples of periodic processes are data acquisition or forecast dissemination. Examples of non-periodic processes include the installation of measurement equipment which starts with a user or component requirement (for example, the order to install a measurement network).

Lastly, the instructions in ISO 9001 give detailed information on the process steps to be referenced in the process description (for example, starting instruction of an AWS). Forms and checklists are helpful tools to reduce the possibility that required tasks will be forgotten.

1.2.3 ISO 9004: Quality management systems – Guidelines for performance improvements

The guidelines for developing the introduced quality management system to achieve business excellence are formulated in ISO 9004. The main aspect is the change from the customer position to the position of interested parties. Different excellence models can be developed by the ISO 9004 guidelines, for example, the Excellence Model of the European Foundation for Quality Management (EFQM)[1] or the Malcolm Baldrige National Quality Award.[2] Both excellence models are appropriately established and well respected in all countries of the world.

The EFQM Excellence Model contains the following nine criteria which are assessed by an expert team of assessors:

---

[1] See EFQM website at http://www.efqm.org.

[2] See the NIST website at http://www.qualiy.nist.gov.

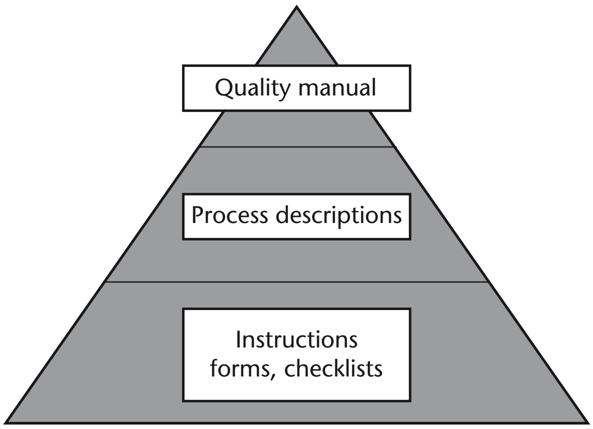


Figure 1.3. The documentation pyramid of a quality management system

(a) Leadership;
(b) People;
(c) Policy and strategy;
(d) Partnerships and resources;
(e) Processes;
(f) People results;
(g) Customer results;
(h) Society results;
(i) Key performance results.

The Malcolm Baldrige model contains seven criteria similar to the EFQM Excellence Model, as follows:
(a) Leadership;
(b) Strategic planning;
(c) Customer and market focus;
(d) Measurement, analysis, and knowledge management;
(e) Human resources focus;
(f) Process management;
(g) Results.

There is no certification process for this standard, but external assessment provides the opportunity to draw comparisons with other organizations according to the excellence model (see also Figure 1.1).

1.2.4 ISO 19011: Guidelines for quality and/or environmental management systems auditing

This standard is a guide for auditing quality or environmental management systems and does not have any regulatory character. The following detailed activities are described for auditing the organization:
(a) Principles of auditing (ethical conduct, fair presentation, due professional care, independence, evidence-based approach);
(b) Audit planning (establishing and implementing the audit programme);
(c) Audit activities (initiating the audit, preparing and conducting on-site audit activities, preparing the audit report);
(d) Training and education of the auditors (competence, knowledge, soft skills).

The manner in which audits are conducted depends on the objectives and scope of the audit which are set by the management or the audit client. The primary task of the first audit is to check the conformity of the quality management system with the ISO 9001 requirements. Further audits give priority to the interaction and interfaces of the processes.

The audit criteria are the documentation of the quality management system, the process descriptions, the quality manual and the unique individual regulations.

The audit planning published by the organization should specify the relevant departments of the organization, the audit criteria and the audit objectives, place, date and time to ensure a clear assignment of the audits.

1.2.5 ISO/IEC 17025: General requirements for the competence of testing and calibration laboratories

This set of requirements is applicable to facilities, including laboratories and testing sites, that wish to have external accreditation of their competence in terms of their measurement and testing processes.

The ISO/IEC 17025 standard aligns its management requirements with those of ISO 9001. This standard is divided into two main parts: management requirements and technical requirements. Hence, the quality management system must follow the requirements of the ISO 9001 standard, which include described processes, a management handbook that provides a connection between processes and goals and policy statements, and that these aspects be audited regularly. All laboratory processes must be approved, verified and validated in a suitable manner to meet the requirements. Furthermore, the roles of the quality management representative (quality manager) and the head of the laboratory must be determined.

An essential component of the technical requirements is the development of uncertainty analyses for each of the measurement processes, including documented and verified traceability to international metrology standards.

1.2.6 ISO/IEC 20000: Information technology – Service management

NMHSs make use of IT equipment to obtain data from the measuring networks to use in GME/LM models and to provide forecasters with the outputs of models. The recommendations of this standard are helpful for the implementation of reliable IT services. The new ISO/IEC 20000 standard summarizes the old British standard BS-15000 and the IT Infrastructure Library (ITIL) recommendations. The division of requirements follows the ITIL structure.

The ITIL elements are divided into service delivery and service support with the following processes:

Service delivery:
(a) Service-level management;
(b) Financial management;
(c) IT service continuity management;
(d) Availability management;
(e) Capacity management.

Service support:
(a) Change management;
(b) Incident management;
(c) Problem management;
(d) Release management;
(e) Configuration management.

Security management is common to both areas.

All these require that:
(a) The processes be adapted to the NMHS's organization;
(b) Particular attention be paid to user support.

Special attention has been placed on the change-management process, which can contain release and configuration management. Incident and problem management is normally covered by the implementation of a user help desk.

1.2.7 WMO Quality Management Framework

The WMO Quality Management Framework gives the basic recommendations that were based on the experiences of NMHSs. The necessary conditions for successful certification against ISO 9001 are explained in WMO (2005*a*; 2005*b*).

The Quality Management Framework is the guide for NMHSs, especially for NMHSs with little experience in a formal quality management system. The introduction of a quality management system is described only briefly in the following section, noting that WMO cannot carry out any certification against ISO 9001.

1.3 INTRODUCTION OF QUALITY MANAGEMENT

The introduction of successful quality management depends heavily on the cooperation of senior management. The senior management of the NMHS must be committed to the quality management system and support the project team. The necessary conditions for successful certification are summarized and the terms of ISO 9001 standards are explained in ISO 20000.

Senior-level management defines a quality policy and the quality objectives (including a quality management commitment), and staff have to be trained in sufficient quality management topics to understand the basis for the quality management process (see section 1.2.2). Most importantly, a project team should be established to manage the transition to a formal quality management system including definition and analysis of the processes used by the organization.

To assist the project team, brief instructions can be given to the staff involved in the process definition, and these would normally include the following:
(a) To document (write down) what each group does;
(b) To indicate the existing documentation;

(c) To indicate the proof or indicators of what is done;
(d) To identify what can be done to continually improve the processes.

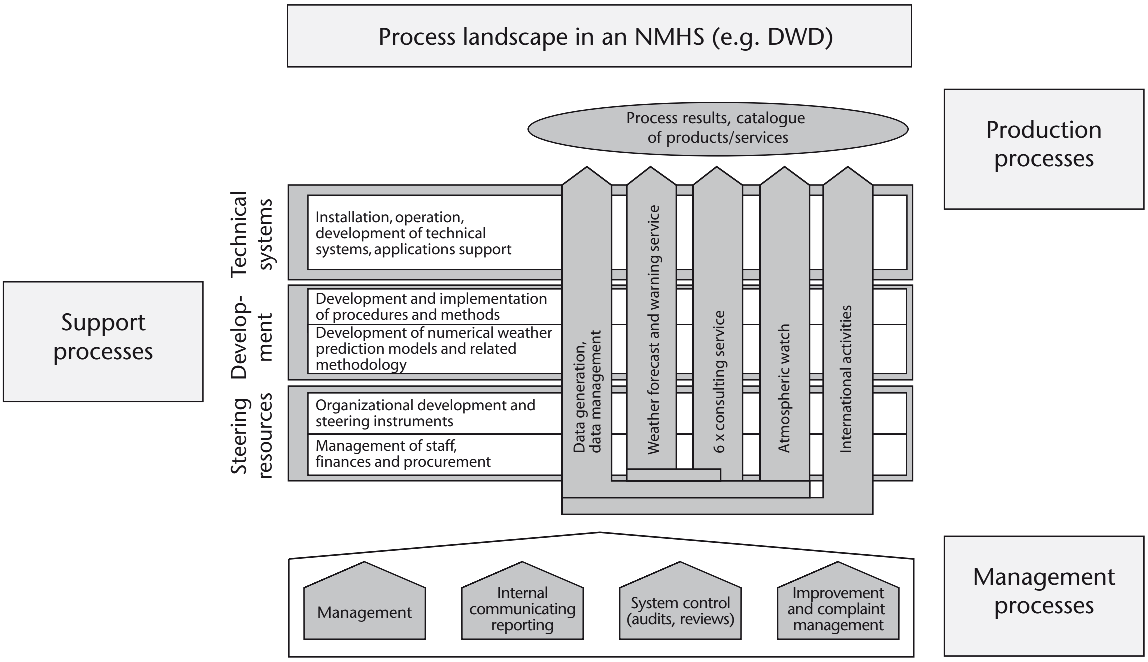
Given that the documentation specifies what the organization does, it is essential that the main processes reflect the functions of the organization of the NMHS. These can be a part of the named processes (see Figure 1.4), for example:
(a) Weather forecasting (including hydrometerological, agrometeorological, human biometeorological aspects) and weather warnings;
(b) Consulting services (including climate and environment);
(c) Data generation (from measurement and observational networks);
(d) International affairs;
(e) Research and development (global modelling, limited area models, instrumentation);
(f) Technical infrastructure (computing and communications, engineering support, data management and IT support);
(g) Administration processes (purchasing, financial and personnel management, organization, administration offices and immovables, knowledge management, central planning and control and legal affairs).

Even though these processes will meet the individual needs of NMHSs and provide them with subprocesses, normally there should be regulations for remedying incidents (for example, system failures, staff accidents).

The processes must be introduced into the organization with clear quality objectives, and all staff must be trained in understanding the processes, including the use of procedures and checklists and the measurement of process indicators.

Before applying for certification, the quality management sytem must be reviewed by carrying out internal audits in the departments and divisions of the organization, to check conformity of the quality management system as stated and as enacted. These documented reviews can be performed on products by specialized and trained auditors. The requirements and recommendations for these reviews are given in ISO 19011 (see section 1.2.4).

The management review of the quality management system will include the following:
(a) Audit results;
(b) Customer feedback;
(c) Process performance based on performance indicators;



DWD = Deutscher Wetterdienst

Figure. 1.4. Process landscape of an NMHS (example: DWD, WMO 2005*a*)

(d) Status of preventive and corrective actions;
(e) Follow-up actions from previous management reviews;
(f) Changes in the quality management system (policy of the organization);
(g) Recommendations for improvement.

1.4 ACCREDITATION OF LABORATORIES

Accreditation requires additional processes and documentation and, most importantly, evidence that laboratory staff have been trained and have mastered the processes and methods to be accredited.

The documentation must contain the following aspects:
(a) A management manual for the laboratory;
(b) The process descriptions mentioned in section 1.2;
(c) The documentation of all processes and methods;
(d) Work instructions for all partial steps in the processes and methods;
(e) Equipment manuals (manual including calibrating certificates);
(f) Maintenance manuals.

Since procedures and methods are likely to change more frequently than the management aspects of the accreditation, the methods are usually not included in the management manual. However, there is specific reference to the procedures and methods used in the management manual.

As it is unlikely that all aspects of the accreditation will be covered once the quality management system is introduced, it is recommended that a pre-audit be conducted and coordinated with the certifying agency. In these pre-audits it would be normal for the certifying agency:
(a) To assess staff and spatial prerequisites;
(b) To assess the suitability of the management system;
(c) To check the documentation;
(d) To validate the scope of the accreditation.

The accreditation procedure consists of assessments by an expert panel (external to the organization), which includes a representative from the certifying agency. The assessment panel will focus on two main areas as follows:
(a) Documentation;
(b) An examination of the facilities included in the scope of the accreditation (for example, laboratories, special field sites).

The assessment of documentation covers verification of the following documents:
(a) A management manual (or laboratory guide);
(b) Procedure instructions;
(c) Work instructions;
(d) Test instructions;
(e) Equipment manuals;
(f) Maintenance manuals;
(g) Uncertainty analyses of specific quantities, test results and calibrations;
(h) Proof documents (for example, that staff training has occurred and that quantities are traceable);
(i) Records (for example, correspondence with the customer, generated calibration certificates).

The external expert team could request additional documents, as all aspects of the ISO/EC 17025 standard are checked and in more detail than a certification under ISO 9001.

Besides the inspection of the measurement methods and associated equipment, the assessment of the facilities in the scope of the accreditation will include the following:
(a) Assessment of the staff (including training and responsibility levels);
(b) Assessment of the infrastructure that supports the methods (for example, buildings, access).

The following are also checked during the assessment to ensure that they meet the objectives required by management for accreditation:
(a) Organizational structure;
(b) Staff qualifications;
(c) Adequacy of the technological facilities;
(d) Customer focus.

In addition, the assessment should verify that the laboratory has established proof of the following:
(a) Technical competence (choice and use of the measuring system);
(b) Calibration of measurement equipment;
(c) Maintenance of measurement equipment;
(d) Verification and validation of methods.

Benefits and disadvantages of accreditation

Through initial accreditation by an independent certifying agency NMHSs prove their competence in the area of meteorological measuring and testing methods according to a recognized standard. Once accreditation is established, there is an ongoing periodic external audit, which provides additional proof that standards have been maintained, but more importantly it helps the organization to ensure that its own internal quality requirements are met.

An accreditation with suitable scope also provides commercial opportunities for the calibration, verification and assessment of measurement devices.

For organizations that do not have a quality management system in place, the benefits of accreditation are significant. First, it documents the organization's system, and, through that, a process of analysis can be used to make the organization more efficient and effective. For example, one component of accreditation under ISO/EC 17025 requires uncertainty analyses for every calibration and verification test; such quantitative analyses provide information on where the most benefit can be achieved for the least resources.

Accreditation or certification under any recognized quality framework requires registration and periodic audits by external experts and the certifying agency. These represent additional costs for the organization and are dependent on the scope of the accreditation and certification.

Seeking accreditation before an effective quality management system is in place will lead to an increased use of resources and result in existing resources being diverted to establish a quality management system; there will also be additional periodic audit costs.

1.5 QUALITY MANAGEMENT TOOLS

Several well known tools exist to assist in the processes of a quality management system and its continuous improvement. Three examples of these tools are described below as an introduction: the Balanced Score card, Failure Mode and Effects Analysis, and Six Sigma.

The Balanced Scorecard (Kaplan and Norton, 1996) has at a minimum four points of focus: finances, the customer, processes and employees. Often the general public is added given that public interests must always be taken into account.

Each organization and organization element provides key performance indicators for each of the focus areas, which in turn link to the organization's mission (or purpose, vision or goals) and the strategy (or working mission and vision).

Failure Mode and Effects Analysis is a method for the examination of possible missing causes and faults and the probability of their appearance. The method can be used for analysing production processes and product specification. The aim of the optimization process is to reduce the risk priority number.

The Six Sigma method was developed in the communications industry and uses statistical process controls to improve production. The objective of this method is to reduce process failure below a specific value.

1.6 FACTORS AFFECTING DATA QUALITY

The life history of instruments in field service involves different phases, such as planning according to user requirements, selection and installation of equipment, operation, calibration, maintenance and training activities. To obtain data of adequate or prescribed quality, appropriate actions must be taken at each of these phases. Factors affecting data quality are summarized in this section, and reference is made to more comprehensive information available in other chapters of this Guide and in other WMO Manuals and Guides.

User requirements: The quality of a measuring system can be assessed by comparing user requirements with the ability of the systems to fulfil them. The compatibility of user data-quality requirements with instrumental performance must be considered not only at the design and planning phase of a project, but also continually during operation, and implementation must be planned to optimize cost/benefit and cost/performance ratios. This involves a shared responsibility between users, instrument experts and logistic experts to match technical and financial factors. In particular, instrument experts must study the data quality requirements of the users to be able to propose specifications within the technical state of the art. This important phase of design is called value analysis. If it is neglected, as is often the case, it is likely that the cost or quality requirements, or both, will not be satisfied, possibly to such an extent that the project will fail and efforts will have been wasted.

Functional and technical specifications: The translation of expressed requirements into functional specifications and then into technical specifications is a very important and complex task, which requires a sound knowledge of user requirements, meteorological measuring technology, methods of observation, WMO regulations, and relevant operational conditions and technical/administrative infrastructures. Because the specifications will determine the general functioning of a planned measuring system, their impact on data quality is considerable.

Selection of instruments: Instruments should be carefully selected considering the required uncertainty, range and resolution (for definitions see Part I, Chapter 1), the climatological and environmental conditions implied by the users' applications, the working conditions, and the available technical infrastructure for training, installation and maintenance. An inappropriate selection of instruments may yield poor quality data that may not be anticipated, causing many difficulties when they are subsequently discovered. An example of this is an underspecification resulting in excessive wear or drift. In general, only high quality instruments should be employed for meteorological purposes. Reference should be made to the relevant information given in the various chapters in this Guide. Further information on the performance of several instruments can be found in the reports of WMO international instrument intercomparisons and in the proceedings of WMO/CIMO and other international conferences on instruments and methods of observation.

Acceptance tests: Before installation and acceptance, it is necessary to ensure that the instruments fulfil the original specifications. The performance of instruments, and their sensitivity to influence factors, should be published by manufacturers and are sometimes certified by calibration authorities. However, WMO instrument intercomparisons show that instruments may still be degraded by factors affecting their quality which may appear during the production and transportation phases. Calibration errors are difficult or impossible to detect when adequate standards and appropriate test and calibration facilities are not readily available. It is an essential component of good management to carry out appropriate tests under operational conditions before instruments are used for operational purposes. These tests can be applied both to determine the characteristics of a given model and to control the effective quality of each instrument.

When purchasing equipment, consideration should be given to requiring the supplier to set up certified quality assurance procedures within its organization according to the requirements of the NMHS, thus reducing the need for acceptance testing by the recipient. The extra cost when purchasing equipment may be justified by consequent lower costs for internal testing or operational maintenance, or by the assured quality of subsequent field operations.

Compatibility: Data compatibility problems can arise when instruments with different technical characteristics are used for taking the same types of measurements. This can happen, for example, when changing from manual to automated measurements, when adding new instruments of different time-constants, when using different sensor shielding, when applying different data reduction algorithms, and so on. The effects on data compatibility and homogeneity should be carefully investigated by long-term intercomparisons. Reference should be made to the various WMO reports on international instrument intercomparisons.

Siting and exposure: The density of meteorological stations depends on the timescale and space scale of the meteorological phenomena to be observed and is generally specified by the users, or set by WMO regulations. Experimental evidence exists showing that improper local siting and exposure can cause a serious deterioration in the accuracy and representativeness of measurements. General siting and exposure criteria are given in Part I, Chapter 1, and detailed information appropriate to specific instruments is given in the various chapters of Part I. Further reference should be made to the regulations in WMO (2003). Attention should also be paid to external factors that can introduce errors, such as dust, pollution, frost, salt, large ambient temperature extremes or vandalism.

Instrumental errors: A proper selection of instruments is a necessary, but not sufficient, condition for obtaining good-quality data. No measuring technique is perfect, and all instruments produce various systematic and random errors. Their impact on data quality should be reduced to an acceptable level by appropriate preventive and corrective actions. These errors depend on the type of observation; they are discussed in the relevant chapters of this Guide (see Part I).

Data acquisition: Data quality is not only a function of the quality of the instruments and their correct siting and exposure, but also depends on the techniques and methods used to obtain data and to convert them into representative data. A distinction should be made between automated measurements and human observations. Depending on the technical characteristics of a sensor, in particular its time-constant, proper sampling and averaging procedures must be applied. Unwanted sources of external electrical interference and noise can degrade the quality of the sensor output and should be eliminated by proper sensor-signal conditioning before entering the data-acquisition system. Reference should be made to sampling and filtering in Part II, Chapter 1 and in Part II, Chapter 2. In the case of manual instrument readings, errors may arise from the design, settings or resolution of the instrument, or from the inadequate training of the observer. For visual or subjective observations, errors can occur through an inexperienced observer misinterpreting the meteorological phenomena.

Data processing: Errors may also be introduced by the conversion techniques or computational procedures applied to convert the sensor data into Level II or Level III data. Examples of this are the calculation of humidity values from measured relative humidity or dewpoint and the reduction of pressure to mean sea level. Errors also occur during the coding or transcription of meteorological messages, in particular if performed by an observer.

Real-time quality control: Data quality depends on the real-time quality-control procedures applied during data acquisition and processing and during the preparation of messages, in order to eliminate the main sources of errors. These procedures are specific to each type of measurement but generally include gross checks for plausible values, rates of change and comparisons with other measurements (for example, dewpoint cannot exceed temperature). Special checks concern manually entered observations and meteorological messages. In AWSs, special built-in test equipment and software can detect specific hardware errors. The application of these procedures is most important since some errors introduced during the measuring process cannot be eliminated later. For an overview of manual and automatic methods in use, refer to other paragraphs of this chapter as well as to Part II, Chapter 1 and WMO (1989; 1992; 1993*a*; 2003).

Performance monitoring: As real-time quality-control procedures have their limitations and some errors can remain undetected, such as long-term drifts in sensors and errors in data transmission, performance monitoring at the network level is required at meteorological analysis centres and by network managers. This monitoring is described in section 1.8 of this chapter. Information can also be found in Part II, Chapter 1 and in WMO (1989). It is important to establish effective liaison procedures between those responsible for monitoring and for maintenance and calibration, to facilitate rapid response to fault or failure reports from the monitoring system.

Testing and calibration: During their operation, the performance and instrumental characteristics of meteorological instruments change for reasons such as the ageing of hardware components, degraded maintenance, exposure, and so forth. These may cause long-term drifts or sudden changes in calibration. Consequently, instruments need regular inspection and calibration to provide reliable data. This requires the availability of standards and of appropriate calibration and test facilities. It also requires an efficient calibration plan and calibration housekeeping. See Part III, Chapter 4 for general information about test and calibration aspects and to the relevant chapters of Part I for individual instruments.

Maintenance: Maintenance can be corrective (when parts fail), preventive (such as cleaning or lubrication) or adaptive (in response to changed requirements or obsolescence). The quality of the data provided by an instrument is considerably affected by the quality of its maintenance, which in turn depends mainly on the ability of maintenance personnel and the maintenance concept. The capabilities, personnel and equipment of the organization or unit responsible for maintenance must be adequate for the instruments and networks. Several factors have to be considered, such as a maintenance plan, which includes corrective, preventive and adaptive maintenance, logistic management, and the repair, test and support facilities. It must noted that the maintenance costs of equipment can greatly exceed its purchase costs (see Part II, Chapter 1).

Training and education: Data quality also depends on the skills of the technical staff in charge of testing, calibration and maintenance activities, and of the observers making the observations. Training and education programmes should be organized according to a rational plan geared towards meeting the needs of users, and especially the maintenance and calibration requirements outlined above, and should be adapted to the system; this is particularly important for AWSs. As part of the system procurement, the manufacturer should be obliged to provide very comprehensive operational and technical documentation and to organize operational and technical training courses (see Part III, Chapter 5) in the NMHS.

Metadata: A sound quality assurance entails the availability of detailed information on the observing system itself and in particular on all changes that occur during the time of its operation. Such information on data, known as metadata, enables the operator of an observing system to take the most appropriate preventive, corrective and adaptive actions to maintain or enhance data quality. Metadata requirements are further considered in section 1.9. For further information on metadata, see Part I, Chapter 1 (and Annex 1.C).

1.7 QUALITY ASSURANCE (QUALITY CONTROL)

WMO (2003) prescribes that certain quality-control procedures must be applied to all meteorological data to be exchanged internationally. Level I and Level II data, and the conversion from one to the other, must be subjected to quality control. WMO (1992) prescribes that quality-control procedures must be applied by meteorological data processing centres to most kinds of weather reports exchanged internationally, to check for coding errors, internal consistency, time and space consistency, and physical and climatological limits, and it specifies the minimum frequency and times for quality control.

WMO (1989) gives general guidance on procedures. It emphasizes the importance of quality control at the station, because some errors occurring there cannot be subsequently corrected, and also points out the great advantages of automation. WMO (1993*a*) gives rather detailed descriptions of the procedures that may be used by numerical analysis centres, with advice on climatological limits, types of internal consistency checks, comparisons with neighbouring stations and with analyses and prognoses, and provides brief comments on the probabilities of rejecting good data and accepting false data with known statistical distributions of errors.

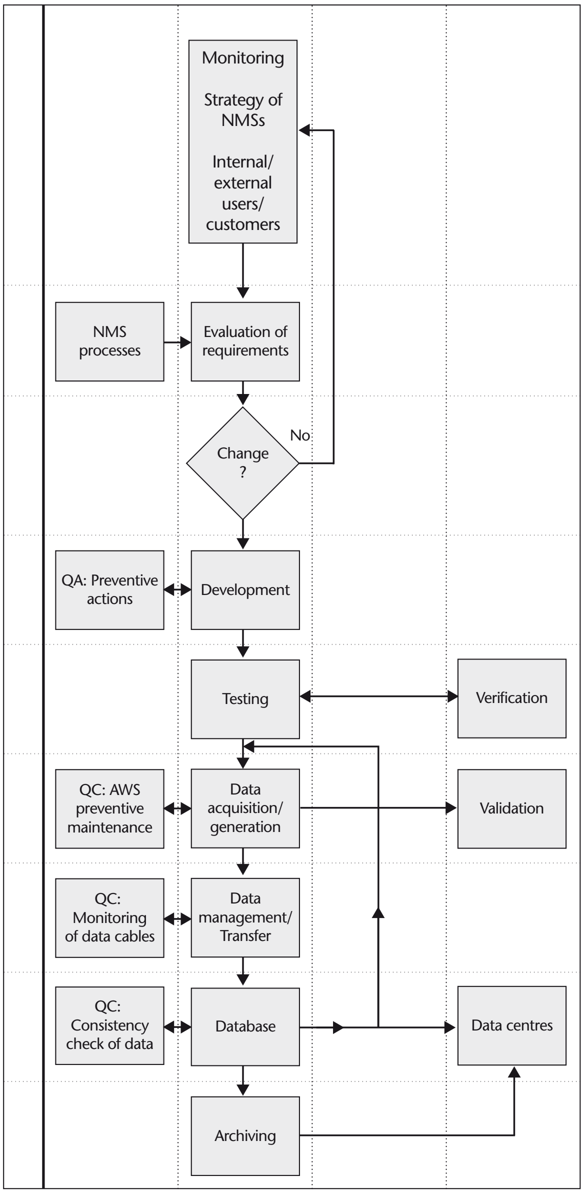
Quality control, as specifically defined in section 1.1, is implemented in real time or near-real time to data acquisition and processing. In practice, responsibility for quality control is assigned to various points along the data chain. These may be at the station, if there is direct manual involvement in data acquisition, or at the various centres where the data are processed.

Quality assurance procedures must be introduced and reassessed during the development phases of new sensors or observing systems (see Figure 5).

1.7.1 Surface data

1.7.1.1 Manual observations and staffed stations

The observer or the officer in charge at a station is expected to ensure that the data leaving the station have been quality controlled, and should be



NMS: National Meteorological or Hydrological Service
QA: Quality assurance
QC: Quality control

Figure 1.5. Process for observation generation

provided with established procedures for attending to this responsibility. This is a specific function, in addition to other maintenance and record-keeping functions, and includes the following:

(a) Internal consistency checks of a complete synoptic or other compound observation: In practice, they are performed as a matter of course by an experienced observer, but they should nevertheless be an explicit requirement. Examples of this are the relations between the temperature, the dewpoint and the daily extremes, and between rain, cloud and weather;
(b) Climatological checks: These for consistency: The observer knows, or is provided with charts or tables of, the normal seasonal ranges of variables at the station, and should not allow unusual values to go unchecked;
(c) Temporal checks: These should be made to ensure that changes since the last observation are realistic, especially when the observations have been made by different observers;
(d) Checks of all arithmetical and table look-up operations;
(e) Checks of all messages and other records against the original data.

1.7.1.2 Automatic weather stations

At AWSs, some of the above checks should be performed by the software, as well as engineering checks on the performance of the system. These are discussed in Part II, Chapter 1.

1.7.2 Upper-air data

The procedures for controlling the quality of upper-air data are essentially the same as those for surface data. Checks should be made for internal consistency (such as lapse rates and shears), for climatological and temporal consistency, and for consistency with normal surface observations. For radiosonde operations, it is of the utmost importance that the baseline initial calibration be explicitly and deliberately checked. The message must also be checked against the observed data.

The automation of on-station quality control is particularly useful for upper-air data.

1.7.3 Data centres

Data should be checked in real time or as close to real time as possible, at the first and subsequent points where they are received or used. It is highly advisable to apply the same urgent checks to all data, even to those that are not used in real time, because later quality control tends to be less effective. If available, automation should of course be used, but certain quality-control procedures are possible without computers, or with only partial assistance by computing facilities. The principle is that every message should be checked, preferably at each stage of the complete data chain.

The checks that have already been performed at stations are usually repeated at data centres, perhaps in more elaborate form by making use of automation. Data centres, however, usually have access to other network data, thus making a spatial check possible against observations from surrounding stations or against analysed or predicted fields. This is a very powerful method and is the distinctive contribution of a data centre.

If errors are found, the data should be either rejected or corrected by reference back to the source, or should be corrected at the data centre by inference. The last of these alternatives may evidently introduce further errors, but it is nevertheless valid in many circumstances; data so corrected should be flagged in the database and should be used only carefully.

The quality-control process produces data of established quality, which may then be used for real-time operations and for a databank. However, a by-product of this process should be the compilation of information about the errors that were found. It is good practice to establish at the first or subsequent data-processing point a system for immediate feedback to the origin of the data if errors are found, and to compile a record for use by the network manager in performance monitoring, as discussed below. This function is best performed at the regional level, where there is ready access to the field stations.

The detailed procedures described in WMO (1993*a*) are a guide to controlling the quality control of data for international exchange, under the recommendations of WMO (1992).

1.7.4 Interaction with field stations

If quality is to be maintained, it is absolutely essential that errors be tracked back to their source, with some kind of corrective action. For data from staffed stations this is very effectively done in near-real time, not only because the data may be corrected, but also to identify the reason for the error and prevent it from recurring.

It is good practice to assign a person at a data centre or other operational centre with the responsibility for maintaining near-real-time communication and effective working relations with the field stations, to be used whenever errors in the data are identified.

1.8 PERFORMANCE MONITORING

The management of a network, or of a station, is greatly strengthened by keeping continuous records of performance, typically on a daily and monthly schedule. The objective of performance monitoring is to review continually the quality of field stations and of each observing system, such as for pressure measurement, or the radiosonde network.

There are several aspects to performance monitoring, as follows:

(a) Advice from data centres should be used to record the numbers and types of errors detected by quality-control procedures;

(b) Data from each station should be compiled into synoptic and time-section sets. Such sets should be used to identify systematic differences from neighbouring stations, both in spatial fields and in comparative time series. It is useful to derive statistics of the mean and the scatter of the differences. Graphical methods are effective for these purposes;

(c) Reports should be obtained from field stations about equipment faults, or other aspects of performance.

These types of records are very effective in identifying systematic faults in performance and in indicating corrective action. They are powerful indicators of many factors that affect the data, such as exposure or calibration changes, deteriorating equipment, changes in the quality of consumables or the need for retraining. They are particularly important for maintaining confidence in automatic equipment.

The results of performance monitoring should be used for feedback to the field stations, which is important to maintain motivation. The results also indicate when action is necessary to repair or upgrade the field equipment.

Performance monitoring is a time-consuming task, to which the network manager must allocate adequate resources. WMO (1988) describes a system to monitor data from an AWS network, using a small, dedicated office with staff monitoring real-time output and advising the network managers and data users. Miller and Morone (1993) describe a system with similar functions, in near-real time, making use of a mesoscale numerical model for the spatial and temporal tests on the data.

1.9 DATA HOMOGENEITY AND METADATA

In the past, observational networks were primarily built to support weather forecasting activities. Operational quality control was focused mainly on identifying outliers, but rarely incorporated checks for data homogeneity and continuity of time series. The surge of interest in climate change, primarily as a result of concerns over increases in greenhouse gases, changed this situation. Data homogeneity tests have revealed that many of the apparent climate changes can be attributed to inhomogeneities in time series caused only by operational changes in observing systems. This section attempts to summarize these causes and presents some guidelines concerning the necessary information on data, namely, metadata, which should be made available to support data homogeneity and climate change investigations.

1.9.1 Causes of data inhomogeneities

Inhomogeneities caused by changes in the observing system appear as abrupt discontinuities, gradual changes, or changes in variability. Abrupt discontinuities mostly occur due to changes in instrumentation, siting and exposure changes, station relocation, changes in the calculation of averages, data reduction procedures and the application of new calibration corrections. Inhomogeneities that occur as a gradually increasing effect may arise from a change in the surroundings of the station, urbanization and gradual changes in instrumental characteristics. Changes in variability are caused by instrument malfunctions. Inhomogeneities are further due to changes in the time of observations, insufficient routine inspection, maintenance and calibration, and unsatisfactory observing procedures. On a network level, inhomogeneities can be caused by data incompatibilities. It is obvious that all factors affecting data quality also cause data inhomogeneities.

The historical survey of changes in radiosondes (WMO, 1993*b*) illustrates the seriousness of the problem and is a good example of the careful work that is necessary to eliminate it.

Changes in the surface-temperature record when manual stations are replaced by AWSs, and changes in the upper-air records when radiosondes are changed, are particularly significant cases of data inhomogeneities. These two cases are now well recognized and can, in principle, be anticipated and corrected, but performance monitoring can be used to confirm the effectiveness of corrections, or even to derive them.

1.9.2 Metadata

Data inhomogeneities should, as far as possible, be prevented by appropriate quality-assurance procedures with respect to quality control. However, this cannot always be accomplished as some causes of inhomogeneities, such as the replacement of a sensor, can represent real improvements in measuring techniques. It is important to have information on the occurrence, type and, especially, the time of all inhomogeneities that occur. After obtaining such information, climatologists can run appropriate statistical programs to link the previous data with the new data in homogeneous databases with a high degree of confidence. Information of this kind is commonly available in what is known as metadata — information on data — also called station histories. Without such information, many of the above-mentioned inhomogeneities may not be identified or corrected. Metadata can be considered as an extended version of the station administrative record, containing all possible information on the initial set-up, and type and times of changes that occurred during the life history of an observing system. As computer data management systems are an important aspect of quality data delivery, it is desirable that metadata should be available as a computer database enabling computerized composition, updating and use.

1.9.3 Elements of a metadata database

A metadata database contains initial set-up information together with updates whenever changes occur. Major elements include the following:

(a) Network information:
The operating authority, and the type and purpose of the network;

(b) Station information:
  (i) Administrative information;
  (ii) Location: geographical coordinates, elevation(s);[3]
  (iii) Descriptions of remote and immediate surroundings and obstacles;[3]
  (iv) Instrument layout;[3]
  (v) Facilities: data transmission, power supply, cabling;
  (vi) Climatological description;

(c) Individual instrument information:
  (i) Type: manufacturer, model, serial number, operating principles;
  (ii) Performance characteristics;
  (iii) Calibration data and time;
  (iv) Siting and exposure: location, shielding, height above ground;[3]
  (v) Measuring or observing programme;
  (vi) Times of observations;
  (vii) Observer;
  (viii) Data acquisition: sampling, averaging;
  (ix) Data-processing methods and algorithms;
  (x) Preventive and corrective maintenance;
  (xi) Data quality (in the form of a flag or uncertainty).

1.9.4 Recommendations for a metadata system

The development of a metadata system requires considerable interdisciplinary organization, and its operation, particularly the scrupulous and accurately dated record of changes in the metadata base, requires constant attention.

A useful survey of requirements is given in WMO (1994), with examples of the effects of changes in observing operations and an explanation of the advantages of good metadata for obtaining a reliable climate record from discontinuous data. The basic functional elements of a system for maintaining a metadatabase may be summarized as follows:

(a) Standard procedures must be established for collecting overlapping measurements for all significant changes made in instrumentation, observing practices and sensor siting;
(b) Routine assessments must be made of ongoing calibration, maintenance, and homogeneity problems for the purpose of taking corrective action, when necessary;
(c) There must be open communication between the data collector and the researcher to provide feedback mechanisms for recognizing data problems, the correction or at least the potential for problems, and the improvement of, or addition to, documentation to meet initially unforeseen user requirements (for example, work groups);
(d) There must be detailed and readily available documentation on the procedures, rationale, testing, assumptions and known problems involved in the construction of the data set from the measurements.

---

[3] It is necessary to include maps and plans on appropriate scales.

These four recommendations would have the effect of providing a data user with enough metadata to enable manipulation, amalgamation and summarization of the data with minimal assumptions regarding data quality and homogeneity.

1.10 NETWORK MANAGEMENT

All the factors affecting data quality described in section 1.6 are the subject of network management. In particular, network management must include corrective action in response to the network performance revealed by quality-control procedures and performance monitoring.

Networks are defined in WMO (2003), and guidance on network management in general terms is given in WMO (1989), including the structure and functions of a network management unit. Network management practices vary widely according to locally established administrative arrangements.

It is highly desirable to identify a particular person or office as the network manager to whom operational responsibility is assigned for the impact of the various factors on data quality. Other specialists who may be responsible for the management and implementation of some of these factors must collaborate with the network manager and accept responsibility for their effect on data quality.

The manager should keep under review the procedures and outcomes associated with all of the factors affecting quality, as discussed in section 1.6, including the following considerations:

(a) The quality-control systems described in section 1.1 are operationally essential in any meteorological network and should receive priority attention by the data users and by the network management;
(b) Performance monitoring is commonly accepted as a network management function. It may be expected to indicate the need for action on the effects of exposure, calibration and maintenance. It also provides information on the effects of some of the other factors;
(c) Field station inspection described below, is a network management function;
(d) Equipment maintenance may be a direct function of the network management unit. If not, there should be particularly effective collaboration between the network manager and the office responsible for the equipment;
(e) The administrative arrangements should enable the network manager to take, or arrange for, corrective action arising from quality-control procedures, performance monitoring, the inspection programme, or any other factor affecting quality. One of the most important other factors is observer training, as described in Part III, Chapter 5, and the network manager should be able to influence the content and conduct of courses and how they are conducted or the prescribed training requirements.

1.10.1 Inspections

Field stations should be inspected regularly, preferably by specially appointed, experienced inspectors. The objectives are to examine and maintain the work of the observers, the equipment and instrument exposure, and also to enhance the value of the data by recording the station history. At the same time, various administrative functions, which are particularly important for staffed stations, can be performed. The same principles apply to staffed stations, stations operated by part-time, voluntary or contract observers and, to a certain degree, to AWSs. Requirements for inspections are laid down in WMO (2003), and advice is given in WMO (1989).

Inspections reports are part of the performance monitoring record.

It is highly advisable to have a systematic and exhaustive procedure fully documented in the form of inspections and maintenance handbooks, to be used by the visiting inspectors. Procedures should include the details of subsequent reporting and follow-up.

The inspector should attend, in particular, to the following aspects of station operations:

(a) *Instrument performance*: Instruments requiring calibration must be checked against a suitable standard. Atmospheric pressure is the prime case, as all field barometers can drift to some degree. Mechanical and electrical recording systems must be checked according to established procedures. More complex equipment such as AWSs and radars need various physical and electrical checks. Anemometers and thermometer shelters are particularly prone to deterioration of various kinds, which may vitiate the data. The physical condition of all equipment should be examined for dirt, corrosion and so on;

(b) *Observing methods*: Bad practice can easily occur in observing procedures, and the work of all observers should be continually reviewed. Uniformity in methods recording and coding is essential for synoptic and climatological use of the data;
(c) *Exposure*: Any changes in the surroundings of the station must be documented and corrected in due course, if practicable. Relocation may be necessary.

Inspections of manual stations also serve the purpose of maintaining the interest and enthusiasm of the observers. The inspector must be tactful, informative, enthusiastic and able to obtain willing cooperation.

A prepared form for recording the inspection should be completed for every inspection. It should include a checklist on the condition and installation of the equipment and on the ability and competence of the observers. The inspection form may also be used for other administrative purposes, such as an inventory.

It is most important that all changes identified during the inspection should be permanently recorded and dated so that a station history can be compiled for subsequent use for climate studies and other purposes.

An optimum frequency of inspection visits cannot be generally specified, even for one particular type of station. It depends on the quality of the observers and equipment, the rate at which the equipment and exposure deteriorates, and changes in the station staff and facilities. An inspection interval of two years may be acceptable for a well-established station, and six months may be appropriate for automatic stations. Some kinds of stations will have special inspection requirements.

Some equipment maintenance may be performed by the inspector or by the inspection team, depending on the skills available. In general, there should be an equipment maintenance programme, as is the case for inspections. This is not discussed here because the requirements and possible organizations are very diverse.

REFERENCES AND FURTHER READING

Deming, W.E., 1986: *Out of the Crisis: Quality, Productivity and Competitive Position*. University of Cambridge Press, Cambridge.

International Organization for Standardization, 2005: *Quality management systems – Fundamentals and vocabulary* . ISO 9000:2005.

International Organization for Standardization, 2000: *Quality management systems – Requirements*. ISO 9001:2000.

International Organization for Standardization, 2000: *Quality management systems – Guidelines for performance improvements*. ISO 9004:2000.

International Organization for Standardization, 2002: *Guidelines for quality and/or environmental management systems auditing*. ISO 19011:2002.

International Organization for Standardization International Electrotechnical Commission, 2005: *General requirements for the competence of testing and calibration laboratories*. ISO/EC 17025:2005.

International Organization for Standardization International Electrotechnical Commission, 2005: *Information technology – Service management – Part 1: Specification*. ISO/IEC 20000-1:2005.

International Organization for Standardization: Information technology – Service management – Part 2: Code of practice, ISO/IEC 20000-2:2005-12, Geneva

Kaplan, R.S., D.P. Norton, 1996: *The Balanced Scorecard*: *Translating Strategy into Action*. Harvard Business School Press, Boston.

Miller, P.A. and L.L. Morone, 1993: Real-time quality control of hourly reports from the automated surface observing system. *Preprints of the Eighth Symposium on Meteorological Observations and Instrumentation*. American Meteorological Society, Boston, pp. 373-38.

World Meteorological Organization, 1988: Practical experience of the operation of quality evaluation programmes for automated surface observations both on land and over the sea (M. Field and J. Nash). *Papers Presented at the WMO Technical Conference on Instruments and Methods of Observation (TECO-1988).* Instruments and Observing Methods Report No. 33, WMO/TD-No. 222, Geneva, pp. 335-340.

World Meteorological Organization, 1989: *Guide on the Global Observing and forecasting System*. WMO-No. 488, Geneva.

World Meteorological Organization, 1992: *Manual on the Global Data-processing System*. WMO-No. 485, Geneva.

World Meteorological Organization, 1993*a*: *Guide on the Global Data-Processing System*. WMO-No. 305, Geneva.

World Meteorological Organization, 1993*b*: *Historical Changes in Radiosonde Instruments and Practices* (D.J. Gaffen). Instruments and Observing Methods Report No. 50, WMO/TD-No. 541, Geneva.

World Meteorological Organization, 1994: Homogeneity of data and the climate record (K.D. Hadeen and N.B. Guttman). *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, pp. 3–11.

World Meteorological Organization, 2003: *Manual on the Global Observing System*. Volume I, WMO-No. 544, Geneva.

World Meteorological Organization, 2005*a*: *Quality Management Framework (QMF)*. First WMO Technical Report (revised edition), WMO/TD-No. 1268.

World Meteorological Organization, 2005*b*: *Guidelines on Quality Management Procedures and Practices for Public Weather Services*. PWS-11, WMO/TD No. 1256, Geneva.

CHAPTER 2

SAMPLING METEOROLOGICAL VARIABLES

2.1 GENERAL

The purpose of this chapter is to give an introduction to this complex subject, for non-experts who need enough knowledge to develop a general understanding of the issues and to acquire a perspective of the importance of the techniques.

Atmospheric variables such as wind speed, temperature, pressure and humidity are functions of four dimensions – two horizontal, one vertical, and one temporal. They vary irregularly in all four, and the purpose of the study of sampling is to define practical measurement procedures to obtain representative observations with acceptable uncertainties in the estimations of mean and variability.

Discussion of sampling in the horizontal dimensions includes the topic of areal representativeness, which is discussed in Part I, Chapter 1, in other chapters on measurements of particular quantities, and briefly below. It also includes the topics of network design, which is a special study related to numerical analysis, and of measurements of area-integrated quantities using radar and satellites; neither of these is discussed here. Sampling in the vertical is briefly discussed in Part I, Chapters 12 and 13 and Part II, Chapter 5. This chapter is therefore concerned only with sampling in time, except for some general comments about representativeness.

The topic can be addressed at two levels as follows:

(a) At an elementary level, the basic meteorological problem of obtaining a mean value of a fluctuating quantity representative of a stated sampling interval at a given time, using instrument systems with long response times compared with the fluctuations, can be discussed. At the simplest level, this involves consideration of the statistics of a set of measurements, and of the response time of instruments and electronic circuits;

(b) The problem can be considered more precisely by making use of the theory of time-series analysis, the concept of the spectrum of fluctuations, and the behaviour of filters. These topics are necessary for the more complex problem of using relatively fast-response instruments to obtain satisfactory measurements of the mean or the spectrum of a rapidly varying quantity, wind being the prime example.

It is therefore convenient to begin with a discussion of time series, spectra and filters in sections 2.2 and 2.3. Section 2.4 gives practical advice on sampling. The discussion here, for the most part, assumes digital techniques and automatic processing.

It is important to recognize that an atmospheric variable is actually never sampled. It is only possible to come as close as possible to sampling the output of a sensor of that variable. The distinction is important because sensors do not create an exact analogue of the sensed variable. In general, sensors respond more slowly than the atmosphere changes, and they add noise. Sensors also do other, usually undesirable, things such as drift in calibration, respond non-linearly, interfere with the quantity that they are measuring, fail more often than intended, and so on, but this discussion will only be concerned with response and the addition of noise.

There are many textbooks available to give the necessary background for the design of sampling systems or the study of sampled data. See, for example, Bendat and Piersol (1986) or Otnes and Enochson (1978). Other useful texts include Pasquill and Smith (1983), Stearns and Hush (1990), Kulhánek (1976), and Jenkins and Watts (1968).

2.1.1 Definitions

For the purposes of this chapter the following definitions are used:

Sampling is the process of obtaining a discrete sequence of measurements of a quantity.

A *sample* is a single measurement, typically one of a series of spot readings of a sensor system. Note that this differs from the usual meaning in statistics of a set of numbers or measurements which is part of a population.

An *observation* is the result of the sampling process, being the quantity reported or recorded (often also called a measurement). In the context of time-series analysis, an observation is derived from a number of samples.

The ISO definition of a *measurement* is a "set of operations having the object of determining the value of a quantity". In common usage, the term may be used to mean the value of either a sample or an observation.

The *sampling time* or *observation period* is the length of the time over which one observation is made, during which a number of individual samples are taken.

The *sampling interval* is the time between successive observations.

The *sampling function* or *weighting function* is, in its simplest definition, an algorithm for averaging or filtering the individual samples.

The *sampling frequency* is the frequency at which samples are taken. The *sample spacing* is the time between samples.

Smoothing is the process of attenuating the high frequency components of the spectrum without significantly affecting the lower frequencies. This is usually done to remove noise (random errors and fluctuations not relevant for the application).

A *filter* is a device for attenuating or selecting any chosen frequencies. Smoothing is performed by a *low-pass* filter, and the terms *smoothing* and *filtering* are often used interchangeably in this sense. However, there are also *high-pass* and *band-pass* filters. Filtering may be a property of the instrument, such as inertia, or it may be performed electronically or numerically.

2.1.2 Representativeness in time and space

Sampled observations are made at a limited rate and for a limited time interval over a limited area. In practice, observations should be designed to be sufficiently frequent to be representative of the unsampled parts of the (continuous) variable, and are often taken as being representative of a longer time interval and larger area.

The user of an observation expects it to be representative, or typical, of an area and time, and of an interval of time. This area, for example, may be "the airport" or that area within a radius of several kilometres and within easy view of a human observer. The time is the time at which the report was made or the message transmitted, and the interval is an agreed quantity, often 1, 2 or 10 min.

To make observations representative, sensors are exposed at standard heights and at unobstructed locations and samples are processed to obtain mean values. In a few cases, sensors, for example transmissometers, inherently average spatially, and this contributes to the representativeness of the observation. The human observation of visibility is another example of this. However, the remaining discussion in this chapter will ignore spatial sampling and concentrate upon time sampling of measurements taken at a point.

A typical example of sampling and time averaging is the measurement of temperature each minute (the samples), the computation of a 10 min average (the sampling interval and the sampling function), and the transmission of this average (the observation) in a synoptic report every 3 h. When these observations are collected over a period from the same site, they themselves become samples in a new time sequence with a 3 h spacing. When collected from a large number of sites, these observations also become samples in a spatial sequence. In this sense, representative observations are also representative samples. In this chapter we discuss the initial observation.

2.1.3 The spectra of atmospheric quantities

By applying the mathematical operation known as the Fourier transform, an irregular function of time (or distance) can be reduced to its spectrum, which is the sum of a large number of sinusoids, each with its own amplitude, wavelength (or period or frequency) and phase. In broad contexts, these wavelengths (or frequencies) define "scales" or "scales of motion" of the atmosphere.

The range of these scales is limited in the atmosphere. At one end of the spectrum, horizontal scales cannot exceed the circumference of the Earth or about 40 000 km. For meteorological purposes, vertical scales do not exceed a few tens of kilometres. In the time dimension, however, the longest scales are climatological and, in principle, unbounded, but in practice the longest period does not exceed the length of records. At the short end, the viscous dissipation of turbulent energy into heat sets a lower bound. Close to the surface of the Earth, this bound is at a wavelength of a few centimetres and increases with height to a few metres in the stratosphere. In the time dimension, these wavelengths correspond to frequencies of tens of hertz. It is correct to say that atmospheric variables are bandwidth limited.

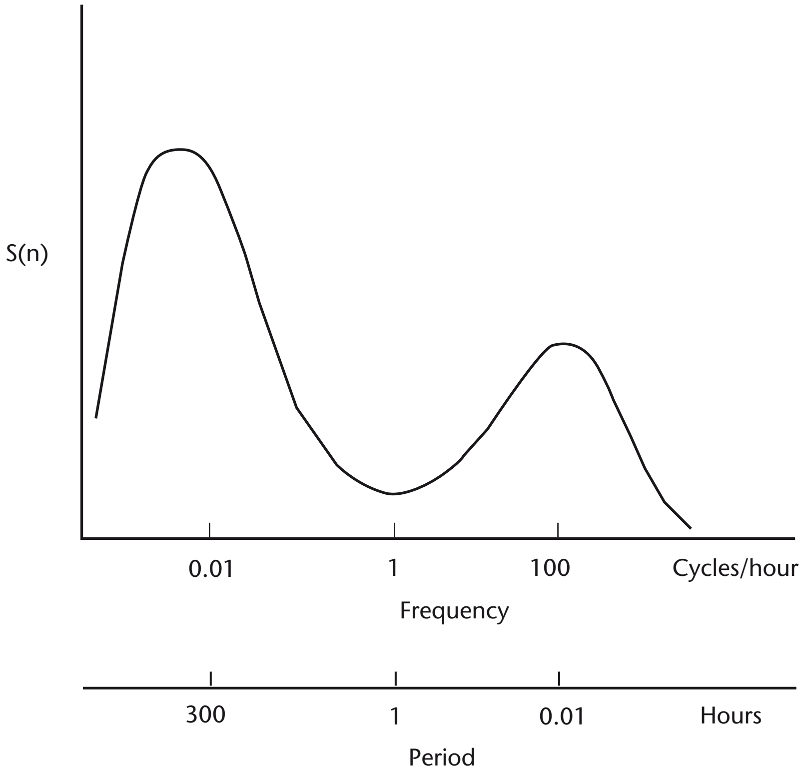


Figure 2.1. A typical spectrum of a meteorological quantity

Figure 2.1 is a schematic representation of a spectrum of a meteorological quantity such as wind, notionally measured at a particular station and time. The ordinate, commonly called energy or spectral density, is related to the variance of the fluctuations of wind at each frequency *n*. The spectrum in Figure 2.1 has a minimum of energy at the mesoscale around one cycle per hour, between peaks in the synoptic scale around one cycle per four days, and in the microscale around one cycle per minute. The smallest wavelengths are a few centimetres and the largest frequencies are tens of hertz.

2.2 TIME SERIES, POWER SPECTRA AND FILTERS

This section is a layperson's introduction to the concepts of time-series analysis which are the basis for good practice in sampling. In the context of this Guide, they are particularly important for the measurement of wind, but the same problems arise for temperature, pressure and other quantities. They became important for routine meteorological measurements when automatic measurements were introduced, because frequent fast sampling then became possible. Serious errors can occur in the estimates of the mean, the extremes and the spectrum if systems are not designed correctly.

Although measurements of spectra are non-routine, they have many applications. The spectrum of wind is important in engineering, atmospheric dispersion, diffusion and dynamics. The concepts discussed here are also used for quantitative analysis of satellite data (in the horizontal space dimension) and in climatology and micrometeorology.

In summary, the argument is as follows:

(a) An optimum sampling rate can be assessed from consideration of the variability of the quantity being measured. Estimates of the mean and other statistics of the observations will have smaller uncertainties with higher sampling frequencies, namely, larger samples;

(b) The Nyquist theorem states that a continuous fluctuating quantity can be precisely determined by a series of equispaced samples if they are sufficiently close together;

(c) If the sampling frequency is too low, fluctuations at the higher unsampled frequencies (above the Nyquist frequency, defined in section 2.2.1) will affect the estimate of the mean value. They will also affect the computation of the lower frequencies, and the measured spectrum will be incorrect. This is known as aliasing. It can cause serious errors if it is not understood and allowed for in the system design;

(d) Aliasing may be avoided by using a high sampling frequency or by filtering so that a lower, more convenient sampling frequency can be used;

(e) Filters may be digital or analogue. A sensor with a suitably long response time acts as a filter.

A full understanding of sampling involves knowledge of power spectra, the Nyquist theorem, filtering and instrument response. This is a highly specialized subject, requiring understanding of the characteristics of the sensors used, the way the output of the sensors is conditioned, processed and logged, the physical properties of the elements being measured, and the purpose to which the analysed data are to be put. This, in turn, may require expertise in the physics of the instruments, the theory of electronic or other systems used in conditioning and logging processes, mathematics, statistics and the meteorology of the phenomena, all of which are well beyond the scope of this chapter.

However, it is possible for a non-expert to understand the principles of good practice in measuring means and extremes, and to appreciate the problems associated with measurements of spectra.

2.2.1 **Time-series analysis**

It is necessary to consider signals as being either in the time or the frequency domain. The fundamental idea behind spectral analysis is the concept of Fourier transforms. A function, *f(t)*, defined between $t = 0$ and $t = \tau$ can be transformed into the sum of a set of sinusoidal functions:

$$f(t) = \sum_{j=0}^{\circ} \left[A_j \sin(jwt) + B_j \cos(jwt)\right] \qquad (2.1)$$

where $\omega = 2\pi/\tau$. The right-hand side of the equation is a Fourier series. A_j and B_j are the amplitudes of the contributions of the components at frequencies $n_j = j\omega$. This is the basic transformation between the time and frequency domains. The Fourier coefficients A_j and B_j relate directly to the frequency $j\omega$ and can be associated with the spectral contributions to *f(t)* at these frequencies. If the frequency response of an instrument is known – that is, the way in which it amplifies or attenuates certain frequencies – and if it is also known how these frequencies contribute to the original signal, the effect of the frequency response on the output signal can be calculated. The contribution of each frequency is characterized by two parameters. These can be most conveniently taken as the amplitude and phase of the frequency component. Thus, if equation 2.1 is expressed in its alternative form:

$$(f(t) = \sum_{j=0}^{\infty} \alpha_j \, sin(j\omega t + \phi_j) \qquad (2.2)$$

the amplitude and phase associated with each spectral contribution are α_j and ϕ_j. Both can be affected in sampling and processing.

So far, it has been assumed that the function *f(t)* is known continuously throughout its range t=0 to t=τ. In fact, in most examples this is not the case; the meteorological variable is measured at discrete points in a time series, which is a series of N samples equally spaced Δt apart during a specified period $\tau = (N-1)\Delta t$. The samples are assumed to be taken instantaneously, an assumption which is strictly not true, as all measuring devices require some time to determine the value they are measuring. In most cases, this is short compared with the sample spacing Δt. Even if it is not, the response time of the measuring system can be accommodated in the analysis, although that will not be addressed here.

When considering the data that would be obtained by sampling a sinusoidal function at times Δt apart, it can be seen that the highest frequency that can be detected is $1/(2\Delta t)$, and that in fact any higher frequency sinusoid that may be present in the time series is represented in the data as having a lower frequency. The frequency $1/(2\Delta t)$ is called the Nyquist frequency, designated here as n_y. The Nyquist frequency is sometimes called the folding frequency. This terminology comes from consideration of aliasing of the data. The concept is shown schematically in Figure 2.2. When a spectral analysis of a time series is made, because of the discrete nature of the data, the contribution to the estimate at frequency n also contains contributions from higher frequencies, namely from $2jn_y \pm n$ (j = 1 to s∞). One way of visualizing this is to consider the frequency domain as if it were folded, in a concertina-like way, at $n = 0$ and $n = n_y$ and so on in steps of n_y. The spectral estimate at each frequency in the range is the sum of all the contributions of those higher frequencies that overlie it.

The practical effects of aliasing are discussed in section 2.4.2. It is potentially a serious problem and should be considered when designing instrument systems. It can be avoided by minimizing, or reducing to zero, the strength of the signal at frequencies above n_y. There are a couple of ways of achieving this. First, the system can contain a low-pass filter that

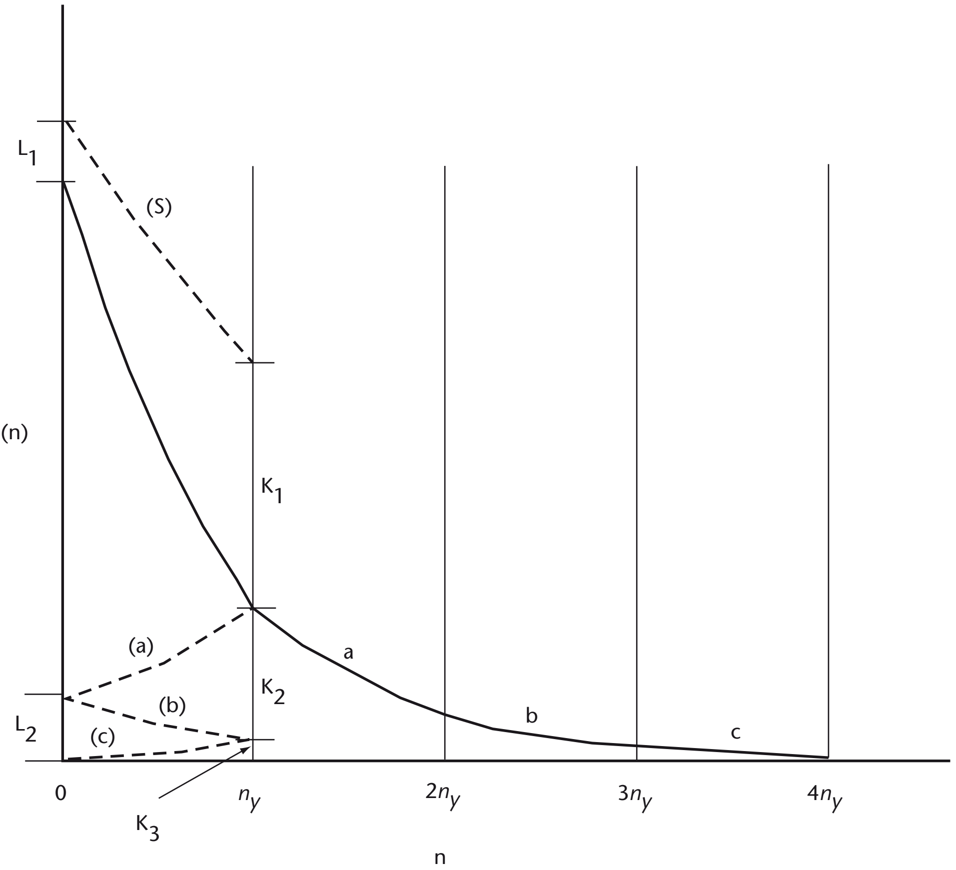


Figure 2.2. A schematic illustration of aliasing a spectrum computed from a stationary time series. The spectrum can be calculated only over the frequency range zero to the Nyquist frequency n_y. The true values of the energies at higher frequencies are shown by the sectors marked a, b and c. These are "folded" back to the $n = 0$ to n_y sector as shown by the broken lines (a), (b), (c). The computed spectrum, shown by the bold broken line (S), includes the sum of these.

attenuates contributions at frequencies higher than n_y before the signal is digitized. The only disadvantage of this approach is that the timing and magnitude of rapid changes will not be recorded well, or even at all. The second approach is to have Δt small enough so that the contributions above the Nyquist frequency are insignificant. This is possible because the spectra of most meteorological variables fall off very rapidly at very high frequencies. This second approach will, however, not always be practicable, as in the example of three-hourly temperature measurements, where if Δt is of the order of hours, small scale fluctuations, of the order of minutes or seconds, may have relatively large spectral ordinates and alias strongly. In this case, the first method may be appropriate.

2.2.2 Measurement of spectra

The spectral density, at least as it is estimated from a time series, is defined as:

$$S(n_j) = (A_j^2 + B_j^2) / n_y = \alpha_j^2 / n_y \qquad (2.3)$$

It will be noted that phase is not relevant in this case.

The spectrum of a fluctuating quantity can be measured in a number of ways. In electrical engineering it was often determined in the past by passing the signal through band-pass filters and by measuring the power output. This was then related to the power of the central frequency of the filter.

There are a number of ways of approaching the numerical spectral analysis of a time series. The most obvious is a direct Fourier transform of the time-series. In this case, as the series is only of finite length, there will be only a finite number of frequency components in the transformation. If there are N terms in the time-series, there will be $N/2$ frequencies resulting from this analysis. A direct calculation is very laborious, and other methods have been developed. The first development was by Blackman and Tukey (1958), who related the auto-correlation function to estimates of various spectral functions. (The auto-correlation function *r(t)* is the correlation coefficient calculated between terms in the time-series separated by a time interval *t*). This was appropriate for the low-powered computing facilities of the 1950s and 1960s, but it has now been generally superseded by the so-called fast Fourier transform (FFT), which takes advantage of the general properties of a digital computer to greatly accelerate the calculations. The main limitation of the method is that the time-series must contain 2^k terms, where k is an integer. In general, this is not a serious problem, as in most instances there are sufficient data to conveniently organize the series to such a length. Alternatively, some FFT computer programs can use an arbitrary number of terms and add synthetic data to make them up to 2^k.

As the time series is of finite duration (*N* terms), it represents only a sample of the signal of interest. Thus, the Fourier coefficients are only an estimate or the true, or population, value. To improve reliability, it is common practice to average a number of terms each side of a particular frequency and to assign this average to the value of that frequency. The confidence interval of the estimate is thereby shrunk. As a rule of thumb, 30° of freedom is suggested as a satisfactory number for practical purposes. Therefore, as each estimate made during the Fourier transform has 2° of freedom (associated with the coefficients of the sine and cosine terms), about 15 terms are usually averaged. Note that 16 is a better number if an FFT approach is used as this is 2^4 and there are then exactly $2(k/^2)^{-4}$ spectral estimates; for example, if there are 1 024 terms in the time series, there will be 512 estimates of the *A*s and *B*s, and 64 smoothed estimates.

Increasingly, the use of the above analyses is an integral part of meteorological systems and relevant not only to the analysis of data. The exact form of spectra encountered in meteorology can show a wide range of shapes. As can be imagined, the contributions can be from the lowest frequencies associated with climate change through annual and seasonal contributions through synoptic events with periods of days, to diurnal and semi-diurnal contributions and local mesoscale events down to turbulence and molecular variations. For most meteorological applications, including synoptic analysis, the interest is in the range minutes to seconds. The spectrum at these frequencies will typically decrease very rapidly with frequency. For periods of less than 1 min, the spectrum often takes values proportional to $n^{-5/3}$. Thus, there is often relatively little contribution from frequencies greater than 1 Hz.

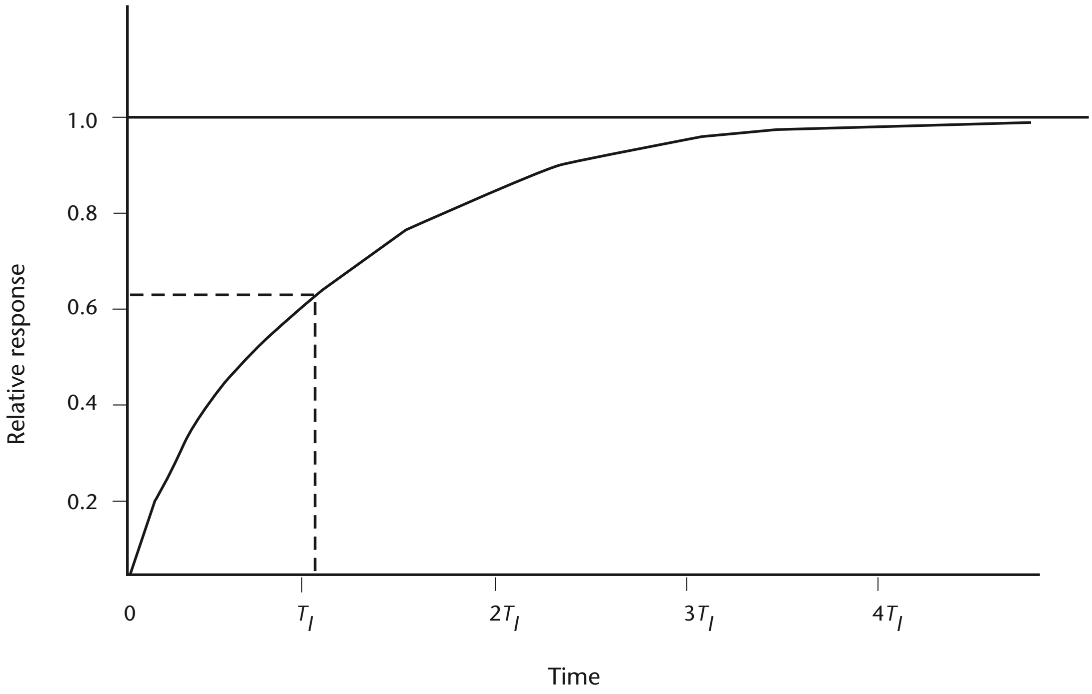


Figure 2.3. The response of a first order system to a step function. At time $T_{(I)}$ the system has reached 63 per cent of its final value.

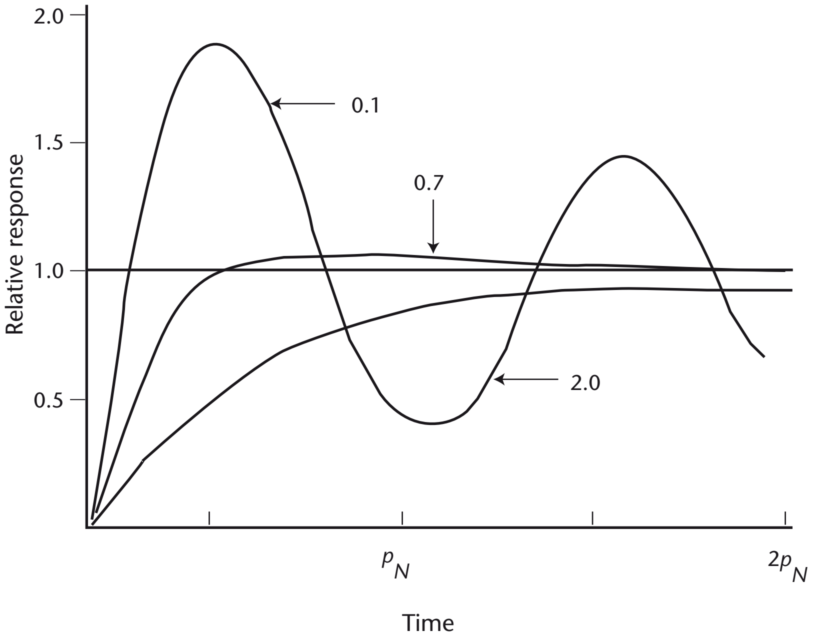


Figure 2.4. The response of a second order system to a step function. p_N is the natural period, related to k_1 in equation 2.7, which, for a wind vane, depends on wind speed. The curves shown are for damping factors with values 0.1 (very lightly damped), 0.7 (critically damped, optimum for most purposes) and 2.0 (heavily damped). The damping factor is related to k_2 in equation 2.7.

One of the important properties of the spectrum is that:

$$\sum_{j=0}^{\infty} S\,(n_j) = \sigma^2 \qquad (2.4)$$

where σ^2 is the variance of the quantity being measured. It is often convenient, for analysis, to express the spectrum in continuous form, so that equation 2.4 becomes:

$$\int_0^{\infty} S(n)\,dn = \sigma^2 \qquad (2.5)$$

It can be seen from equations 2.4 and 2.5 that changes caused to the spectrum, say by the instrument system, will alter the value of σ^2 and hence the statistical properties of the output relative to the input. This can be an important consideration in instrument design and data analysis.

Note also that the left-hand side of equation 2.5 is the area under the curve in Figure 2.2. That area, and therefore the variance, is not changed by aliasing if the time series is stationary, that is if its spectrum does not change from time to time.

2.2.3 **Instrument system response**

Sensors, and the electronic circuits that may be used with them comprising an instrument system, have response times and filtering characteristics that affect the observations.

No meteorological instrument system, or any instrumental system for that matter, precisely follows the quantity it is measuring. There is, in general, no simple way of describing the response of a system, although there are some reasonable approximations to them. The simplest can be classified as first and second order responses. This refers to the order of the differential equation that is used to approximate the way the system responds. For a detailed examination of the concepts that follow, there are many references in physics textbooks and the literature (see MacCready and Jex, 1964).

In the first order system, such as a simple sensor or the simplest low-pass filter circuit, the rate of change of the value recorded by the instrument is directly proportional to the difference between the value registered by the instrument and the true value of the variable. Thus, if the true value at time *t* is *s(t)* and the value measured by the sensor

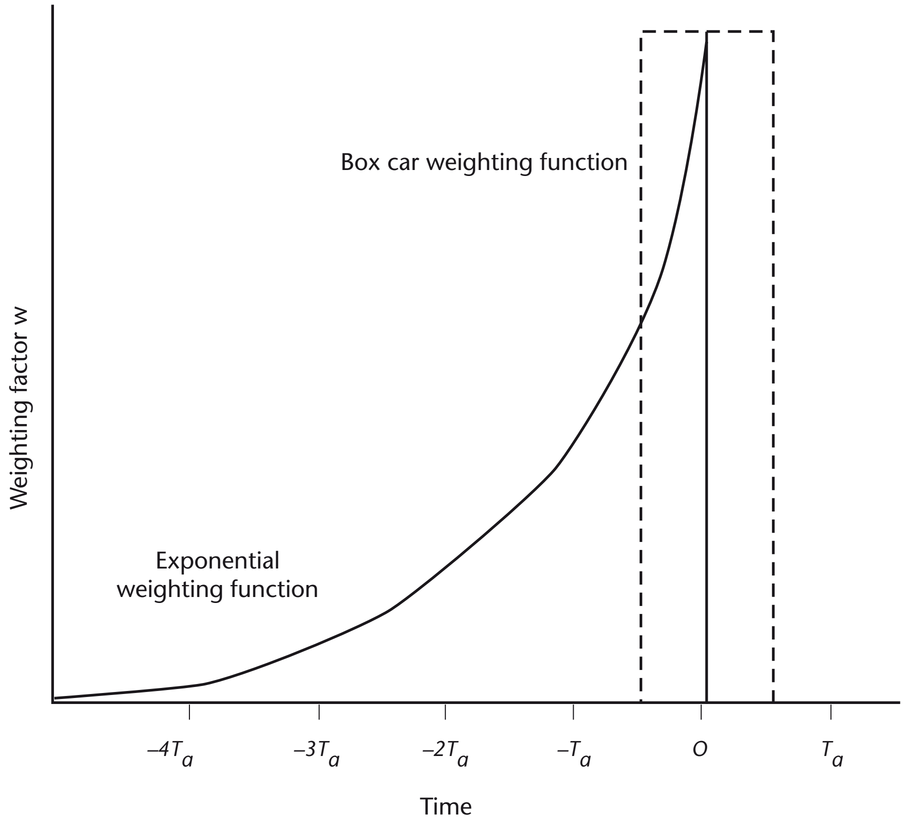


Figure 2.5. The weighting factors for a first order (exponential) weighting function and a box car weighting function. For the box car T_a is T_s, the sampling time, and $w = 1/N$. For the first order function T_a is T_I, the time constant of the filter, and $w(t) = (1/T_I) \exp(-t/T_I)$.

is $s_0(t)$, the system is described by the first order differential equation:

$$\frac{ds_0(t)}{dt} = \frac{s(t) - s_0(t)}{T_I} \qquad (2.6)$$

where T_I is a constant with the dimension of time, characteristic of the system. A first order system's response to a step function is proportional to $\exp(-t/T_I)$, and T_I is observable as the time taken, after a step change, for the system to reach 63 per cent of the final steady reading. Equation 2.6 is valid for many sensors, such as thermometers.

A cup anemometer is a first order instrument, with the special property that T_I is not constant. It varies with wind speed. In fact, the parameter $s_0 T_I$ is called the distance constant, because it is nearly constant. As can be seen in this case, equation 2.6 is no longer a simple first order equation as it is now non-linear and consequently presents considerable problems in its solution. A further problem is that T_I also depends on whether the cups are speeding up or slowing down; that is, whether the right-hand side is positive or negative. This arises because the drag coefficient of a cup is lower if the air-flow is towards the front rather than towards the back.

The wind vane approximates a second order system because the acceleration of the vane toward the true wind direction is proportional to the displacement of the vane from the true direction. This is, of course, the classical description of an oscillator (for example, a pendulum). Vanes, both naturally and by design, are damped. This occurs because of a resistive force proportional to, and opposed to, its rate of change. Thus, the differential equation describing the vane's action is:

$$\frac{d^2\phi_0(t)}{dt^2} = k_1[\phi_0(t) - \phi(t)] - k_2\frac{d\phi_0(t)}{dt} \qquad (2.7)$$

where ϕ is the true wind direction; ϕ_0 is the direction of the wind vane; and k_1 and k_2 are constants. The solution to this is a damped oscillation at the natural frequency of the vane (determined by the constant k_1). The damping of course is very important; it is controlled by the constant k_2. If it is too small, the vane will simply oscillate at the natural frequency; if too great, the vane will not respond to changes in wind direction.

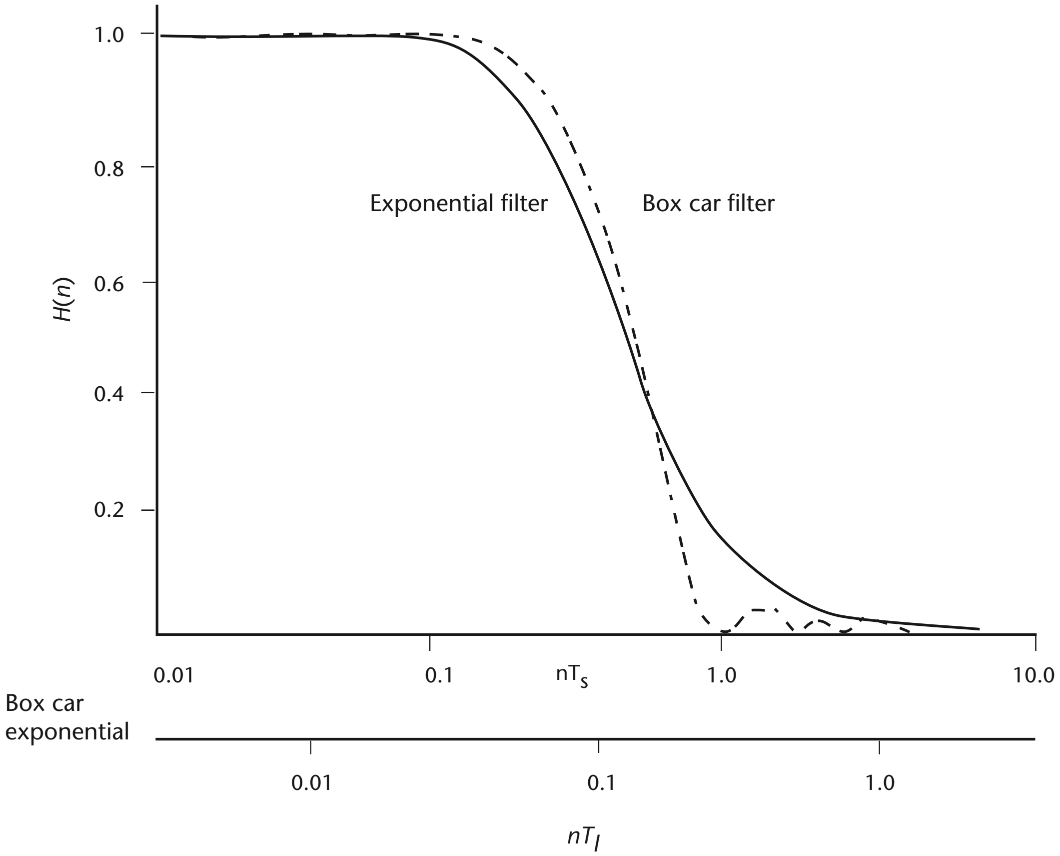


Figure 2.6. Frequency response functions for a first order (exponential) weighting function and a box car weighting function. The frequency is normalized for the first order filter by T_I, the time constant, and for the box car filter by T_s, the sampling time.

It is instructive to consider how these two systems respond to a step change in their input, as this is an example of the way in which the instruments respond in the real world. Equations 2.6 and 2.7 can be solved analytically for this input. The responses are shown in Figures 2.3 and 2.4. Note how in neither case is the real value of the element measured by the system. Also, the choice of the values of the constants k_1 and k_2 can have great effect on the outputs.

An important property of an instrument system is its frequency response function or transfer function *H(n)*. This function gives the amount of the spectrum that is transmitted by the system. It can be defined as:

$$S(n)_{out} = H(n)\, S(n)_{in} \qquad (2.8)$$

where the subscripts refer to the input and output spectra. Note that, by virtue of the relationship in equation 2.5, the variance of the output depends on *H(n)*. *H(n)* defines the effect of the sensor as a filter, as discussed in the next section. The ways in which it can be calculated or measured are discussed in section 2.3.

2.2.4 **Filters**

This section discusses the properties of filters, with examples of the ways in which they can affect the data.

Filtering is the processing of a time series (either continuous or discrete, namely, sampled) in such a way that the value assigned at a given time is weighted by the values that occurred at other times. In most cases, these times will be adjacent to the given time. For example, in a discrete time series of *N* samples numbered 0 to *N*, with value y_i, the value of the filtered observation $\bar{y}_i$ might be defined as:

$$\bar{y}_i = \sum_{j=-m}^{m} w_j \; y_{i+j} \qquad (2.9)$$

Here there are $2m + 1$ terms in the filter, numbered by the dummy variable *j* from $-m$ to $+m$, and $\bar{y}_i$ is centred at $j = 0$. Some data are rejected at the

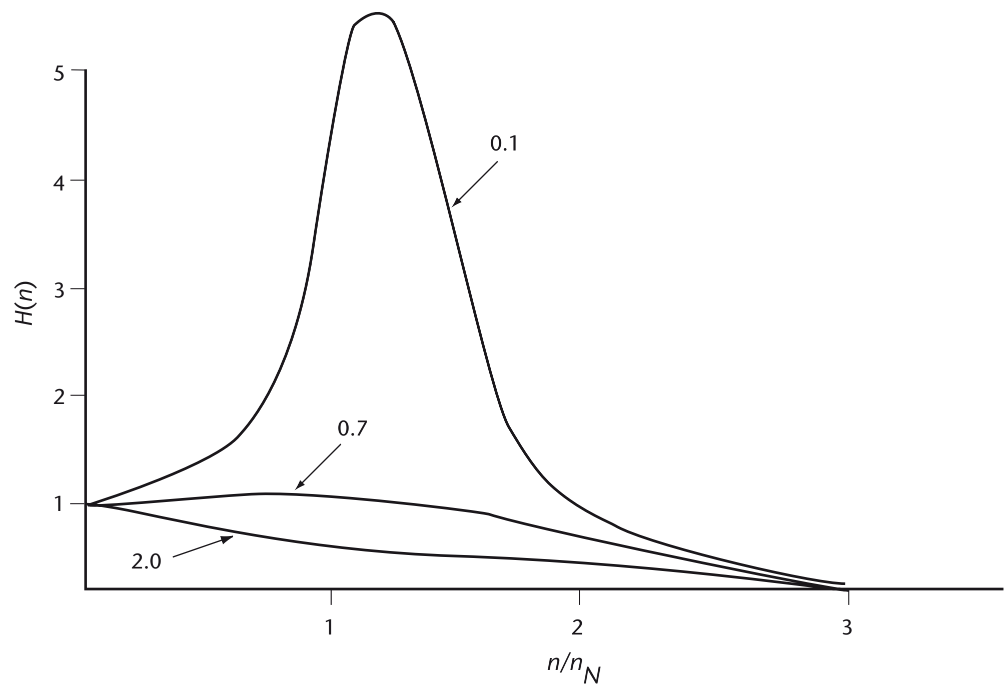


Figure 2.7. Frequency response functions for a second order system, such as a wind vane. The frequency is normalized by n_N, the natural frequency, which depends on wind speed. The curves shown are for damping factors with values 0.1 (very lightly damped), 0.7 (critically damped, optimum for most purposes) and 2.0 (heavily damped).

beginning and end of the sampling time. w_j is commonly referred to as a weighting function and typically:

$$\sum_{j=-m}^{m} w_j = 1 \tag{2.10}$$

so that at least the average value of the filtered series will have the same value as the original one.

The above example uses digital filtering. Similar effects can be obtained using electronics (for example, through a resistor and capacitor circuit) or through the characteristics of the sensor (for example, as in the case of the anemometer, discussed earlier). Whether digital or analogue, a filter is characterized by *H(n)*. If digital, *H(n)* can be calculated; if analogue, it can be obtained by the methods described in section 2.3.

For example, compare a first order system with a response time of T_I, and a "box car" filter of length T_s on a discrete time series taken from a sensor with much faster response. The forms of these two filters are shown in Figure 2.5. In the first, it is as though the instrument has a memory which is strongest at the present instant, but falls off exponentially the further in the past the data goes. The box car filter has all weights of equal magnitude for the period T_s, and zero beyond that. The frequency response functions, *H(n),* for these two are shown in Figure 2.6.

In the figure, the frequencies have been scaled to show the similarity of the two response functions. It shows that an instrument with a response time of, say, 1 s has approximately the same effect on an input as a box car filter applied over 4 s. However, it should be noted that a box car filter, which is computed numerically, does not behave simply. It does not remove all the higher frequencies beyond the Nyquist frequency, and can only be used validly if the spectrum falls off rapidly above n_y. Note that the box car filter shown in Figure 2.6 is an analytical solution for *w* as a continuous function; if the number of samples in the filter is small, the cut-off is less sharp and the unwanted higher frequency peaks are larger.

See Acheson (1968) for practical advice on box car and exponential filtering, and a comparison of their effects.

A response function of a second order system is given in Figure 2.7, for a wind vane in this case, showing how damping acts as a band-pass filter.

It can be seen that the processing of signals by systems can have profound effects on the data output and must be expertly done.

Among the effects of filters is the way in which they can change the statistical information of the data. One of these was touched on earlier and illustrated in equations 2.5 and 2.8. Equation 2.5 shows how the integral of the spectrum over all frequencies gives the variance of the time series, while equation 2.8 shows how filtering, by virtue of the effect of the transfer function, will change the measured spectrum. Note that the variance is not always decreased by filtering. For example, in certain cases, for a second order system the transfer function will amplify parts of the spectrum and possibly increase the variance, as shown in Figure 2.7.

To give a further example, if the distribution is Gaussian, the variance is a useful parameter. If it were decreased by filtering, a user of the data would underestimate the departure from the mean of events occurring with given probabilities or return periods.

Also, the design of the digital filter can have unwanted or unexpected effects. If Figure 2.6 is examined it can be seen that the response function for the box car filter has a series of maxima at frequencies above where it first becomes zero. This will give the filtered data a small periodicity at these frequencies. In this case, the effect will be minimal as the maxima are small. However, for some filter designs quite significant maxima can be introduced. As a rule of thumb, the smaller the number of weights, the greater the problem. In some instances, periodicities have been claimed in data that only existed because the data had been filtered.

An issue related to the concept of filters is the length of the sample. This can be illustrated by noting that, if the length of record is of duration T, contributions to the variability of the data at frequencies below $1/T$ will not be possible. It can be shown that a finite record length has the effect of a high-pass filter. As for the low-pass filters discussed above, a high-pass filter will also have an impact on the statistics of the output data.

2.3 DETERMINATION OF SYSTEM CHARACTERISTICS

The filtering characteristics of a sensor or an electronic circuit, or the system that they comprise, must be known to determine the appropriate sampling frequency for the time series that the system produces. The procedure is to measure the transfer or response function $H(n)$ in equation 2.8.

The transfer function can be obtained in at least three ways – by direct measurement, calculation and estimation.

2.3.1 Direct measurement of response

Response can be directly measured using at least two methods. In the first method a known change, such as a step function, is applied to the sensor or filter and its response time measured; $H(n)$ can then be calculated. In the second method, the output of the sensor is compared to another, much faster sensor. The first method is more commonly used than the second.

A simple example of how to determine the response of a sensor to a known input is to measure the distance constant of a rotating-cup or propellor anemometer. In this example, the known input is a step function. The anemometer is placed in a constant velocity air-stream, prevented from rotating, then released, and its output recorded. The time taken by the output to increase from zero to 63 per cent of its final or equilibrium speed in the air-stream is the time "constant" (see section 2.2.3).

If another sensor, which responds much more rapidly than the one whose response is to be determined, is available, then good approximations of both the input and output can be measured and compared. The easiest device to use to perform the comparison is probably a modern, two-channel digital spectrum analyser. The output of the fast-response sensor is input to one channel, the output of the sensor being tested to the other channel, and the transfer function automatically displayed. The transfer function is a direct description of the sensor as a filter. If the device whose response is to be determined is an electronic circuit, generating a known or even truly random input is much easier than finding a much faster sensor. Again, a modern, two-channel digital spectrum analyser is probably most convenient, but other electronic test instruments can be used.

2.3.2 Calculation of response

This is the approach described in section 2.2.3. If enough is known about the physics of a sensor/filter, the response to a large variety of inputs may

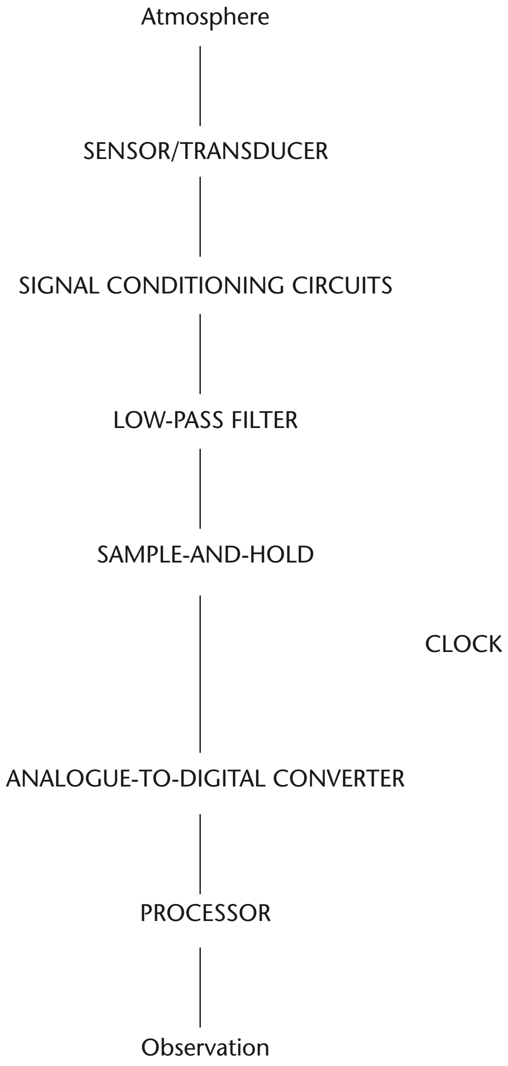


Figure 2.8. An instrument system

be determined by either analytic or numerical solution. Both the response to specific inputs, such as a step function, and the transfer function can be calculated. If the sensor or circuit is linear (described by a linear differential equation), the transfer function is a complete description, in that it describes the amplitude and phase responses as a function of frequency, in other words, as a filter. Considering response as a function of frequency is not always convenient, but the transfer function has a Fourier transform counterpart, the impulse response function, which makes interpretation of response as a function of time much easier. This is illustrated in Figures 2.3 and 2.4 which represent response as a function of time.

If obtainable, analytic solutions are preferable because they clearly show the dependence upon the various parameters.

2.3.3 Estimation of response

If the transfer functions of a transducer and each following circuit are known, their product is the transfer function of the entire system. If, as is usually the case, the transfer functions are low-pass filters, the aggregate transfer function is a low-pass filter whose cut-off frequency is less than that of any of the individual filters.

If one of the individual cut-off frequencies is much less than any of the others, then the cut-off frequency of the aggregate is only slightly smaller.

Since the cut-off frequency of a low-pass filter is approximately the inverse of its time-constant, it follows that, if one of the individual time-constants is much larger than any of the others, the time-constant of the aggregate is only slightly larger.

2.4 SAMPLING

2.4.1 Sampling techniques

Figure 2.8 schematically illustrates a typical sensor and sampling circuit. When exposed to the atmosphere, some property of the transducer changes with an atmospheric variable such as temperature, pressure, wind speed or direction, or humidity and converts that variable into a useful signal, usually electrical. Signal conditioning circuits commonly perform functions such as converting transducer output to a voltage, amplifying, linearizing, offsetting and smoothing. The low-pass filter finalizes the sensor output for the sample-and-hold input. The sample-and-hold and the analogue-to-digital converter produce the samples from which the observation is computed in the processor.

It should be noted that the smoothing performed at the signal conditioning stage for engineering reasons, to remove spikes and to stabilize the electronics, is performed by a low-pass filter; it reduces the response time of the sensor and removes high frequencies which may be of interest. Its effect should be explicitly understood by the designer and user, and its cut-off frequency should be as high as practicable.

So-called “smart sensors”, those with microprocessors, may incorporate all the functions shown. The signal conditioning circuitry may not be found in all sensors, or may be combined with other circuitry. In other cases, such as with a rotating-cup or propellor anemometer, it may be easy to speak only of a sensor because it is awkward to distinguish a transducer. In the few cases for which a transducer or sensor output is a signal whose frequency varies with the atmospheric variable being measured, the sample-and-hold and the analogue-to-digital converter may be replaced by a counter. But these are not important details. The important element in the design is to ensure that the sequence of samples adequately represents the significant changes in the atmospheric variable being measured.

The first condition imposed upon the devices shown in Figure 2.8 is that the sensor must respond quickly enough to follow the atmospheric fluctuations which are to be described in the observation. If the observation is to be a 1, 2 or 10 min average, this is not a very demanding requirement. On the other hand, if the observation is to be that of a feature of turbulence, such as peak wind gust, care must be taken when selecting a sensor.

The second condition imposed upon the devices shown in Figure 2.8 is that the sample-and-hold and the analogue-to-digital converter must provide enough samples to make a good observation. The accuracy demanded of meteorological observations usually challenges the sensor, not the electronic sampling technology. However, the sensor and the sampling must be matched to avoid aliasing. If the sampling rate is limited for technical reasons, the sensor/filter system must be designed to remove the frequencies that cannot be represented.

If the sensor has a suitable response function, the low-pass filter may be omitted, included only as insurance, or may be included because it improves the quality of the signal input to the sample-and-hold. As examples, such a filter may be included to eliminate noise pick-up at the end of a long cable or to further smooth the sensor output. Clearly, this circuit must also respond quickly enough to follow the atmospheric fluctuations of interest.

2.4.2 **Sampling rates**

For most meteorological and climatological applications, observations are required at intervals of 30 min to 24 hours, and each observation is made with a sampling time of the order of 1 to 10 min. Part I, Chapter 1, Annex 1.B gives a recent statement of requirements for these purposes.

A common practice for routine observations is to take one spot reading of the sensor (such as a thermometer) and rely on its time-constant to provide an approximately correct sampling time. This amounts to using an exponential filter (Figure 2.6). Automatic weather stations commonly use faster sensors, and several spot readings must be taken and processed to obtain an average (box car filter) or other appropriately weighted mean.

A practical recommended scheme for sampling rates is as follows:[1]

(a) Samples taken to compute averages should be obtained at equispaced time intervals which:
    (i) Do not exceed the time-constant of the sensor; or
    (ii) Do not exceed the time-constant of an analogue low-pass filter following the linearized output of a fast-response sensor; or
    (iii) Are sufficient in number to ensure that the uncertainty of the average of the samples is reduced to an acceptable level, for example, smaller than the required accuracy of the average;
(b) Samples to be used in estimating extremes of fluctuations, such as wind gusts, should be taken at rates at least four times as often as specified in (i) or (ii) above.

For obtaining averages, somewhat faster sampling rates than (i) and (ii), such as twice per time-constant, are often advocated and practised.

Criteria (i) and (ii) derive from consideration of the Nyquist frequency. If the sample spacing $\Delta t \leq T_I$, the sampling frequency $n \geq 1/T_I$ and $nT_I \geq 1$. It can be seen from the exponential curve in Figure 2.6 that this removes the higher frequencies and prevents aliasing. If $\Delta t = T_I$, $n_y = 1/2T_I$ and the data will be aliased only by the spectral energy at frequencies at $nT_I = 2$ and beyond, that is where the fluctuations have periods of less than $0.5T_I$.

Criteria (i) and (ii) are used for automatic sampling. The statistical criterion in (iii) is more applicable to the much lower sampling rates in manual observations. The uncertainty of the mean is inversely proportional to the square root of the number of observations, and its value can be determined from the statistics of the quantity.

---

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

Criterion (b) emphasizes the need for high sampling frequencies, or more precisely, small time-constants, to measure gusts. Recorded gusts are smoothed by the instrument response, and the recorded maximum will be averaged over several times the time-constant.

The effect of aliasing on estimates of the mean can be seen very simply by considering what happens when the frequency of the wave being measured is the same as the sampling frequency, or a multiple thereof. The derived mean will depend on the timing of the sampling. A sample obtained once per day at a fixed time will not provide a good estimate of mean monthly temperature.

For a slightly more complex illustration of aliasing, consider a time series of three-hourly observations of temperature using an ordinary thermometer. If temperature changes smoothly with time, as it usually does, the daily average computed from eight samples is acceptably stable. However, if a mesoscale event (a thunderstorm) has occurred which reduced the temperature by many degrees for 30 min, the computed average is wrong. The reliability of daily averages depends on the usual weakness of the spectrum in the mesoscale and higher frequencies. However, the occurrence of a higher-frequency event (the thunderstorm) aliases the data, affecting the computation of the mean, the standard deviation and other measures of dispersion, and the spectrum.

The matter of sampling rate may be discussed also in terms of Figure 2.8. The argument in section 2.2.1 was that, for the measurement of spectra, the sampling rate, which determines the Nyquist frequency, should be chosen so that the spectrum of fluctuations above the Nyquist frequency is too weak to affect the computed spectrum. This is achieved if the sampling rate set by the clock in Figure 2.8 is at least twice the highest frequency of significant amplitude in the input signal to the sample-and-hold.

The wording "highest frequency of significant amplitude" used above is vague. It is difficult to find a rigorous definition because signals are never truly bandwidth limited. However, it is not difficult to ensure that the amplitude of signal fluctuations decreases rapidly with increasing frequency, and that the root-mean-square amplitude of fluctuations above a given frequency is either small in comparison with the quantization noise of the analogue-to-digital converter, small in comparison with an acceptable error or noise level in the samples, or contributes negligibly to total error or noise in the observation.

Section 2.3 discussed the characteristics of sensors and circuits which can be chosen or adjusted to ensure that the amplitude of signal fluctuations decreases rapidly with increasing frequency. Most transducers, by virtue of their inability to respond to rapid (high-frequency) atmospheric fluctuations and their ability to replicate faithfully slow (low-frequency) changes, are also low-pass filters. By definition, low-pass filters limit the bandwidth and, by Nyquist's theorem, also limit the sampling rate that is necessary to reproduce the filter output accurately. For example, if there are real variations in the atmosphere with periods down to 100 ms, the Nyquist sampling frequency would be 1 per 50 ms, which is technically demanding. However, if they are seen through a sensor and filter which respond much more slowly, for example with a 10 s time-constant, the Nyquist sampling rate would be 1 sample per 5 s, which is much easier and cheaper, and preferable if measurements of the high frequencies are not required.

2.4.3 Sampling rate and quality control

Many data quality control techniques of use in automatic weather stations depend upon the temporal consistency, or persistence, of the data for their effectiveness. As a very simple example, two hypothetical quality-control algorithms for pressure measurements at automatic weather stations should be considered. Samples are taken every 10 s, and 1 min averages computed each minute. It is assumed that atmospheric pressure only rarely, if ever, changes at a rate exceeding 1 hPa per minute.

The first algorithm rejects the average if it differs from the previous one by more than 1 hPa. This would not make good use of the available data. It allows a single sample with as much as a 6 hPa error to pass undetected and to introduce a 1 hPa error in an observation.

The second algorithm rejects a sample if it differs from the previous one by more than than 1 hPa. In this case, an average contains no error larger than about 0.16 (1/6) hPa. In fact, if the assumption is correct that atmospheric pressure only rarely changes at a rate exceeding 1 hPa per minute, the accept/reject criteria on adjacent samples could be tightened to 0.16 hPa and error in the average could be reduced even more.

The point of the example is that data quality control procedures that depend upon temporal consistency (correlation) for their effectiveness are best applied to data of high temporal resolution (sampling rate). At the high frequency end of the spectrum in the sensor/filter output, correlation between adjacent samples increases with increasing sampling rate until the Nyquist frequency is reached, after which no further increase in correlation occurs.

Up to this point in the discussion, nothing has been said which would discourage using a sensor/filter with a time-constant as long as the averaging period required for the observation is taken as a single sample to use as the observation. Although this would be minimal in its demands upon the digital subsystem, there is another consideration needed for effective data quality control. Observations can be grouped into three categories as follows:

(a) Accurate (observations with errors less than or equal to a specified value);
(b) Inaccurate (observations with errors exceeding a specified value);
(c) Missing.

There are two reasons for data quality control, namely, to minimize the number of inaccurate observations and to minimize the number of missing observations. Both purposes are served by ensuring that each observation is computed from a reasonably large number of data quality-controlled samples. In this way, samples with large spurious errors can be isolated and excluded, and the computation can still proceed, uncontaminated by that sample.

REFERENCES AND FURTHER READING

Acheson, D.T., 1968: An approximation to arithmetic averaging for meteorological variables. *Journal of Applied Meteorology*, Volume 7, pp. 548–553.

Bendat, J.S. and A.G. Piersol, 1986: *Random Data: Analysis and Measurement Procedures*. Second edition, John Wiley and Sons, New York.

Blackman, R.B. and J.W. Tukey, 1958: *The Measurement of Power Spectra*. Dover Publications, New York.

Jenkins, G.M. and D.G. Watts, 1968: *Spectral Analysis and its Applications*. Holden-Day, San Francisco.

Kulhánek, O., 1976: *Introduction to Digital Filtering in Geophysics*. Elsevier, Amsterdam.

MacCready, P.B. and H.R. Jex, 1964: Response characteristics and meteorlogical utilization of propeller and vane wind sensors. *Journal of Applied Meteorology*, Volume 3, Issue 2, pp. 182–193.

Otnes, R.K. and L. Enochson, 1978: *Applied Time Series Analysis*. Volume 1: Basic techniques. John Wiley and Sons, New York.

Pasquill, F. and F.B. Smith, 1983: *Atmospheric Diffusion*. Third edition. Ellis Horwood, Chichester.

Stearns, S.D. and D.R. Hush, 1990: *Digital Signal Analysis*. Second edition. Prentice Hall, New Jersey.

CHAPTER 3

DATA REDUCTION

3.1 GENERAL

This chapter discusses in general terms the procedures for processing and/or converting data obtained directly from instruments into data suitable for meteorological users, in particular for exchange between countries. Formal regulations for the reduction of data to be exchanged internationally have been prescribed by WMO, and are laid down in WMO (2003). Part I, Chapter 1, contains some relevant advice and definitions.

3.1.1 Definitions

In the discussion of the instrumentation associated with the measurement of atmospheric variables, it has become useful to classify the observational data according to data levels. This scheme was introduced in connection with the data-processing system for the Global Atmospheric Research Programme, and is defined in WMO (1992; 2003).

Level I data, in general, are instrument readings expressed in appropriate physical units, and referred to with geographical coordinates. They require conversion to the normal meteorological variables (identified in Part I, Chapter 1). Level I data themselves are in many cases obtained from the processing of electrical signals such as voltages, referred to as raw data. Examples of these data are satellite radiances and water-vapour pressure.

The data recognized as meteorological variables are Level II data. They may be obtained directly from instruments (as is the case for many kinds of simple instruments) or derived from Level I data. For example, a sensor cannot measure visibility, which is a Level II quantity; instead, sensors measure the extinction coefficient, which is a Level I quantity.

Level III data are those contained in internally consistent data sets, generally in grid-point form. They are not within the scope of this Guide.

Data exchanged internationally are Level II or Level III data.

3.1.2 Meteorological requirements

Observing stations throughout the world routinely produce frequent observations in standard formats for exchanging high-quality information obtained by uniform observing techniques, despite the different types of sensors in use throughout the world, or even within nations. To accomplish this, very considerable resources have been devoted over very many years to standardize content, quality and format. As automated observation of the atmosphere becomes more prevalent, it becomes even more important to preserve this standardization and develop additional standards for the conversion of raw data into Level I data, and raw and Level I data into Level II data.

3.1.3 The data reduction process

The role of a transducer is to sense an atmospheric variable and convert it quantitatively into a useful signal. However, transducers may have secondary responses to the environment, such as temperature-dependent calibrations, and their outputs are subject to a variety of errors, such as drift and noise. After proper sampling by a data-acquisition system, the output signal must be scaled and linearized according to the total system calibration and then filtered or averaged. At this stage, or earlier, it becomes raw data. The data must then be converted to measurements of the physical quantities to which the sensor responds, which are Level I data or may be Level II data if no further conversion is necessary. For some applications, additional variables must be derived. At various stages in the process the data may be corrected for extraneous effects, such as exposure, and may be subjected to quality control.

Data from conventional and automatic weather stations (AWSs) must, therefore, be subjected to many operations before they can be used. The whole process is known as data reduction and consists of the execution of a number of functions, comprising some or all of the following:
(a) Transduction of atmospheric variables;
(b) Conditioning of transducer outputs;
(c) Data acquisition and sampling;
(d) Application of calibration information;
(e) Linearization of transducer outputs;

(f) Extraction of statistics, such as the average;
(g) Derivation of related variables;
(h) Application of corrections;
(i) Data quality control;
(j) Data recording and storage;
(k) Compilation of metadata;
(l) Formatting of messages;
(m) Checking message contents;
(n) Transmission of messages.

The order in which these functions are executed is only approximately sequential. Of course, the first and the last function listed above should always be performed first and last. Linearization may immediately follow or be inherent in the transducer, but it must precede the extraction of an average. Specific quality control and the application of corrections could take place at different levels of the data-reduction process. Depending on the application, stations can operate in a diminished capacity without incorporating all of these functions.

In the context of this Guide, the important functions in the data-reduction process are the selection of appropriate sampling procedures, the application of calibration information, linearization when required, filtering and/or averaging, the derivation of related variables, the application of corrections, quality control, and the compilation of metadata. These are the topics addressed in this chapter. More explicit information on quality management is given in Part III, Chapter 1, and on sampling, filtering and averaging in Part III, Chapter 2.

Once reduced, the data must be made available through coding, transmission and receipt, display, and archiving, which are the topics of other WMO Manuals and Guides. An observing system is not complete unless it is connected to other systems that deliver the data to the users. The quality of the data is determined by the weakest link. At every stage, quality control must be applied.

Much of the existing technology and standardized manual techniques for data reduction can also be used by AWSs, which, however, make particular demands. AWSs include various sensors, standard computations for deriving elements of messages, and the message format itself. Not all sensors interface easily with automated equipment. Analytic expressions for computations embodied in tables must be recovered or discovered. The rules for encoding messages must be expressed in computer languages with degrees of precision, completeness and unambiguousness not demanded by natural language instructions prepared for human observers. Furthermore, some human functions, such as the identification of cloud types, cannot be automated using either current or foreseeable technologies.

Data acquisition and data-processing software for AWSs are discussed at some length in Part II, Chapter 1, to an extent which is sufficiently general for any application of electrical transducers in meteorology. Some general considerations and specific examples of the design of algorithms for synoptic AWSs are given in WMO (1987).

In processing meteorological data there is usually one correct procedure, algorithm or approach, and there may be many approximations ranging in validity from good to useless. Experience strongly suggests that the correct approach is usually the most efficient in the long term. It is direct, requires a minimum of qualifications, and, once implemented, needs no further attention. Accordingly, the subsequent paragraphs are largely limited to the single correct approach, as far as exact solutions exist, to the problem under consideration.

3.2 SAMPLING

See Part III, Chapter 2 for a full discussion of sampling. The following is a summary of the main outcomes.

It should be recognized that atmospheric variables fluctuate rapidly and randomly because of ever-present turbulence, and that transducer outputs are not faithful reproductions of atmospheric variables because of their imperfect dynamic characteristics, such as limited ability to respond to rapid changes. Transducers generally need equipment to amplify or protect their outputs and/or to convert one form of output to another, such as resistance to voltage. The circuitry used to accomplish this may also smooth or low-pass filter the signal. There is a cut-off frequency above which no significant fluctuations occur because none exist in the atmosphere and/or the transducer or signal conditioning circuitry has removed them.

An important design consideration is how often the transducer output should be sampled. The definitive answer is: at an equispaced rate at least twice the cut-off frequency of the transducer output signal. However, a simpler and equivalent rule usually suffices: the sampling interval should not exceed the largest of the time-constants of all the devices and circuitry preceding the acquisition system. If the sampling rate is less than twice the cut-off frequency, unnecessary errors occur in the variance of the data and in all derived quantities and statistics. While these increases may be acceptable in particular cases, in others they are not. Proper sampling always ensures minimum variance.

Good design may call for incorporating a low-pass filter, with a time-constant about equal the sampling interval of the data-acquisition system. It is also a precautionary measure to minimize the effects of noise, especially 50 or 60 Hz pick-up from power mains by cables connecting sensors to processors and leakage through power supplies.

3.3 APPLICATION OF CALIBRATION FUNCTIONS

The WMO regulations (WMO, 2003) prescribe that stations be equipped with properly calibrated instruments and that adequate observational and measuring techniques are followed to ensure that the measurements are accurate enough to meet the needs of the relevant meteorological disciplines. The conversion of raw data from instruments into the corresponding meteorological variables is achieved by means of calibration functions. The proper application of calibration functions and any other systematic corrections are most critical for obtaining data that meet expressed accuracy requirements.

The determination of calibration functions should be based on calibrations of all components of the measurement chain. In principle at least, and in practice for some meteorological quantities such as pressure, the calibration of field instruments should be traceable to an international standard instrument, through an unbroken chain of comparisons between the field instrument and some or all of a series of standard instruments, such as a travelling standard, a working standard, a reference standard and a national standard (see Part I, Chapter 1 for definitions).

A description of the calibration procedures and systematic corrections associated with each of the basic meteorological variables is contained in each of the respective chapters in Part I.

Field instruments must be calibrated regularly by an expert, with corresponding revisions to the calibration functions. It is not sufficient to rely on calibration data that is supplied along with the calibration equipment. The supplier's calibration equipment often bears an unknown relationship to the national standard, and, in any case, it must be expected that calibration will change during transport, storage and use. Calibration changes must be recorded in the station's metadata files.

3.4 LINEARIZATION

If the transducer output is not exactly proportional to the quantity being measured, the signal must be linearized, making use of the instrument's calibration. This must be carried out before the signal is filtered or averaged. The sequence of operations "average then linearize" produces different results from the sequence "linearize then average" when the signal is not constant throughout the averaging period.

Non-linearity may arise in the following three ways (WMO, 1987):

(a) Many transducers are inherently nonlinear, namely, their output is not proportional to the measured atmospheric variable. A thermistor is a simple example;

(b) Although a sensor may incorporate linear transducers, the variables measured may not be linearly related to the atmospheric variable of interest. For example, the photodetector and shaft-angle transducer of a rotating beam ceilometer are linear devices, but the ceilometer output signal (backscattered light intensity as a function of angle) is non-linear in cloud height;

(c) The conversion from Level I to Level II may not be linear. For example, extinction coefficient, not visibility or transmittance, is the proper variable to average in order to produce estimates of average visibility.

In the first of these cases, a polynomial calibration function is often used. If so, it is highly desirable to have standardized sensors with uniform calibration coefficients to avoid the problems that arise when interchanging sensors in the field. In the other two cases, an analytic function which describes the behaviour of the transducer is usually appropriate.

3.5 AVERAGING

The natural small-scale variability of the atmosphere makes smoothing or averaging necessary for obtaining representative observations and compatibility of data from different instruments. For international exchange and for many operational applications, the reported measurement must be representative of the previous 2 or 10 min for wind, and, by convention, of 1 to 10 min for other quantities. The 1 min practice arises in part from the fact that some conventional meteorological sensors have a response of the order of 1 min and a single reading is notionally a 1 min average or smoothed value. If the response time of the instrument is much faster, it is necessary to take samples and filter or average them. This is the topic of Part III, Chapter 2. See Part I, Chapter 1, (Annex 1.B), for the requirements of the averaging times typical of operational meteorological instrument systems.

Two types of averaging or smoothing are commonly used, namely, arithmetic and exponential. The arithmetic average conforms with the normal meaning of average and is readily implemented digitally; this is the box car filter described in Part III, Chapter 2. An exponential average is the output of the simplest low-pass filter representing the simplest response of a sensor to atmospheric fluctuations, and it is more convenient to implement in analogue circuitry than the arithmetic average. When the time-constant of a simple filter is approximately half the sampling time over which an average is being calculated, the arithmetic and exponential smoothed values are practically indistinguishable (see Part III, Chapter 2, and also Acheson, 1968).

The outputs of fast-response sensors vary rapidly thus necessitating high sampling rates for optimal (minimum uncertainty) averaging. To reduce the required sampling rate and still provide the optimal digital average, it could be possible to linearize the transducer output (where that is necessary), exponentially smooth it using analogue circuitry with time-constant t_c, and then sample digitally at intervals t_c.

Many other types of elaborate filters, computed digitally, have been used for special applications.

Because averaging non-linear variables creates difficulties when the variables change during the averaging period, it is important to choose the appropriate linear variable to compute the average. The table below lists some specific examples of elements of a synoptic observation which are reported as averages, with the corresponding linear variable that should be used.

3.6 RELATED VARIABLES AND STATISTICS

Besides averaged data, extremes and other variables that are representative for specific periods must be determined, depending on the purpose of the observation. An example of this is wind gust measurements, for which higher sampling rates are necessary.

Also, other quantities have to be derived from the averaged data, such as mean sea-level pressure, visibility and dewpoint. At conventional manual stations, conversion tables are used. It is common practice to incorporate the tables into an AWS and to provide interpolation routines, or to incorporate the basic formulas or approximations of them. See the various chapters of Part I for the data conversion practices, and Part II, Chapter 1 for AWS practice.

Quantities for which data conversion is necessary when averages are being computed

Quantity to be reported	*Quantity to be averaged*
Wind speed and direction	Cartesian components
Dewpoint	Absolute humidity
Visibility	Extinction coefficient

3.7 CORRECTIONS

The measurements of many meteorological quantities have corrections applied to them either as raw data or at the Level I or Level II stage to correct for various effects. These corrections are described in the chapters on the various meteorological variables in Part I. Corrections to raw data, for zero or index error, or for temperature, gravity and the like are derived from the calibration and characterization of the instrument. Other types of corrections or adjustments to the raw or higher level data include smoothing, such as that applied to cloud height measurements and upper-air profiles, and corrections for exposure such as those sometimes applied to temperature, wind and precipitation observations. The algorithms for these types of corrections may, in some cases, be based on studies that are not entirely definitive; therefore, while they no doubt improve the accuracy of the data, the possibility remains that different algorithms may be derived in the future. In such a case, it may become necessary to recover the original uncorrected data. It is, therefore, advisable for the algorithms to be well documented.

3.8 QUALITY MANAGEMENT

Quality management is discussed in Part III, Chapter 1. Formal requirements are specified by WMO (2003) and general procedures are discussed in WMO (1989).

Quality-control procedures should be performed at each stage of the conversion of raw sensor output into meteorological variables. This includes the processes involved in obtaining the data, as well as reducing them to Level II data.

During the process of obtaining data, the quality control should seek to eliminate both systematic and random measurement errors, errors due to departure from technical standards, errors due to unsatisfactory exposure of instruments, and subjective errors on the part of the observer.

Quality control during the reduction and conversion of data should seek to eliminate errors resulting from the conversion techniques used or the computational procedures involved. In order to improve the quality of data obtained at high sampling rates, which may generate increased noise, filtering and smoothing techniques are employed. These are described earlier in this chapter, as well as in Part III, Chapter 2.

3.9 COMPILING METADATA

Metadata are discussed in Part I, Chapter 1, in Part III, Chapter 1, and in other chapters concerning the various meteorological quantities. Metadata must be kept so that:

(a) Original data can be recovered to be re-worked, if necessary (with different filtering or corrections, for instance);
(b) The user can readily discover the quality of the data and the circumstances under which it was obtained (such as exposure);
(c) Potential users can discover the existence of the data.

The procedures used in all the data-reduction functions described above must therefore be recorded, generically for each type of data, and individually for each station and observation type.

REFERENCES AND FURTHER READING

Acheson, D.T., 1968: An approximation to arithmetic averaging for meteorological variables. *Journal of Applied Meteorology,* Volume 7, Issue 4, pp. 548–553.

World Meteorological Organization, 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.

World Meteorological Organization, 1992: M*anual on the Global Data-Processing and Forecasting System*. Volume I, WMO-No. 485, Geneva.

World Meteorological Organization, 1989: Guide on the Global Observing System. WMO-No. 488, Geneva.

World Meteorological Organization, 2003: *Manual on the Global Observing System*. Volume I: Global aspects. WMO-No. 544, Geneva.

CHAPTER 4

TESTING, CALIBRATION AND INTERCOMPARISON

4.1 GENERAL

One of the purposes of WMO, set forth in Article 2 (c) of the WMO Convention, is "to promote standardization of meteorological and related observations and to ensure the uniform publication of observations and statistics". For this purpose, sets of standard procedures and recommended practices have been developed, and their essence is contained in this Guide.

Valid observational data can be obtained only when a comprehensive quality assurance programme is applied to the instruments and the network. Calibration and testing are inherent elements of a quality assurance programme. Other elements include clear definition of requirements, instrument selection deliberately based on the requirements, siting criteria, maintenance and logistics. These other elements must be considered when developing calibration and test plans. On an international scale, the extension of quality assurance programmes to include intercomparisons is important for the establishment of compatible data sets.

Because of the importance of standardization across national boundaries, several WMO regional associations have set up Regional Instrument Centres[1] to organize and assist with standardization and calibration activities. Their terms of reference and locations are given in Part I, Chapter 1, Annex 1.A.

National and international standards and guidelines exist for many aspects of testing and evaluation, and should be used where appropriate. Some of them are referred to in this chapter.

4.1.1 Definitions

Definitions of terms in metrology are given by the International Organization for Standardization (ISO, 1993). Many of them are reproduced in Part I, Chapter 1, and some are repeated here for convenience. They are not universally used and differ in some respects from terminology commonly used in meteorological practice. However, the ISO definitions are recommended for use in meteorology. The ISO document is a joint production with the International Bureau of Weights and Measures, the International Organization of Legal Metrology, the International Electrotechnical Commission, and other similar international bodies.

The ISO terminology differs from common usage in the following respects in particular:

Accuracy (of a measurement) is the closeness of the agreement between the result of a measurement and its true value, and it is a qualitative term. The accuracy of an instrument is the ability of the instrument to give responses close to the true value, and it also is a qualitative term. It is possible to refer to an instrument or a measurement as having a high accuracy, but the quantitative measure of the accuracy is the uncertainty.

Uncertainty is expressed as a measure of dispersion, such as a standard deviation or a confidence level.

The *error* of a measurement is the result minus the true value (the deviation has the other sign), and it is composed of the random and systematic errors (the term *bias* is commonly used for systematic error).

Repeatability is also expressed statistically and is the closeness of agreement of measurements taken under constant (defined) conditions.

Reproducibility is the closeness of agreement under defined different conditions.

ISO does not define precision, and advises against the use of the term.

4.1.2 Testing and calibration programmes

Before using atmospheric measurements taken with a particular sensor for meteorological purposes, the answers to a number of questions are needed as follows:

(a) What is the sensor or system accuracy?
(b) What is the variability of measurements in a network containing such systems or sensors?
(c) What change, or bias, will there be in the data provided by the sensor or system if its siting location is changed?

---

[1] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 19 (CIMO-IX).

(d) What change or bias will there be in the data if it replaces a different sensor or system measuring the same weather element(s)?

To answer these questions and to assure the validity and relevance of the measurements produced by a meteorological sensor or system, some combination of calibration, laboratory testing and functional testing is needed.

Calibration and test programmes should be developed and standardized, based on the expected climatic variability, environmental and electromagnetic interference under which systems and sensors are expected to operate. For example, considered factors might include the expected range of temperature, humidity and wind speed; whether or not a sensor or system must operate in a marine environment, or in areas with blowing dust or sand; the expected variation in electrical voltage and phase, and signal and power line electrical transients; and the expected average and maximum electromagnetic interference. Meteorological Services may purchase calibration and test services from private laboratories and companies, or set up test organizations to provide those services.

It is most important that at least two like sensors or systems be subjected to each test in any test programme. This allows for the determination of the expected variability in the sensor or system, and also facilitates detecting problems.

4.2 TESTING

4.2.1 The purpose of testing

Sensors and systems are tested to develop information on their performance under specified conditions of use. Manufacturers typically test their sensors and systems and in some cases publish operational specifications based on their test results. However, it is extremely important for the user Meteorological Service to develop and carry out its own test programme or to have access to an independent testing authority.

Testing can be broken down into environmental testing, electrical/electromagnetic interference testing and functional testing. A test programme may consist of one or more of these elements.

In general, a test programme is designed to ensure that a sensor or system will meet its specified performance, maintenance and mean-time-between-failure requirements under all expected operating, storage and transportation conditions. Test programmes are also designed to develop information on the variability that can be expected in a network of like sensors, in functional reproducibility, and in the comparability of measurements between different sensors or systems.

Knowledge of both functional reproducibility and comparability is very important to climatology, where a single long-term database typically contains information from sensors and systems that through time use different sensors and technologies to measure the same meteorological variable. In fact, for practical applications, good operational comparability between instruments is a more valuable attribute than precise absolute calibration. This information is developed in functional testing.

Even when a sensor or system is delivered with a calibration report, environmental and possibly additional calibration testing should be performed. An example of this is a modern temperature measurement system, where at present the probe is likely to be a resistance temperature device. Typically, several resistance temperature devices are calibrated in a temperature bath by the manufacturer and a performance specification is provided based on the results of the calibration. However, the temperature system which produces the temperature value also includes of power supplies and electronics, which can also be affected by temperature. Therefore, it is important to operate the electronics and probe as a system through the temperature range during the calibration. It is good practice also to replace the probe with a resistor with a known temperature coefficient, which will produce a known temperature output and operate the electronics through the entire temperature range of interest to ensure proper temperature compensation of the system electronics.

Users should also have a programme for testing randomly selected production sensors and systems, even if pre-production units have been tested, because even seemingly minor changes in material, configurations or manufacturing processes may affect the operating characteristics of sensors and systems.

The International Organization for Standardization has standards (ISO, 1989*a*, 1989*b*) which specify sampling plans and procedures for the inspection of lots of items.

4.2.2 **Environmental testing**

4.2.2.1 **Definitions**

The following definitions serve to introduce the qualities of an instrument system that should be the subject of operational testing:

Operational conditions: Those conditions or a set of conditions encountered or expected to be encountered during the time an item is performing its normal operational function in full compliance with its performance specification.

Withstanding conditions: Those conditions or a set of conditions outside the operational conditions which the instrument is expected to withstand. They may have only a small probability of occurrence during an item's lifetime. The item is not expected to perform its operational function when these withstanding conditions exist. The item is, however, expected to be able to survive these conditions and return to normal performance when the operational conditions return.

Outdoor environment: Those conditions or a set of conditions encountered or expected to be encountered during the time that an item is performing its normal operational function in an unsheltered, uncontrolled natural environment.

Indoor environment: Those conditions or a set of conditions encountered or expected to be encountered during the time that an item is energized and performing its normal operational function within an enclosed operational structure. Consideration is given to both the uncontrolled indoor environment and the artificially controlled indoor environment.

Transportation environment: Those conditions or a set of conditions encountered or expected to be encountered during the transportation portion of an item's life. Consideration is given to the major transportation modes – road, rail, ship and air transportation, and also to the complete range of environments encountered – before and during transportation, and during the unloading phase. The item is normally housed in its packaging/shipping container during exposure to the transportation environment.

Storage environment: Those conditions or a set of conditions encountered or expected to be encountered during the time an item is in its non-operational storage mode. Consideration is given to all types of storage, from the open storage situation, in which an item is stored unprotected and outdoors, to the protected indoor storage situation. The item is normally housed in its packaging/shipping container during exposure to the storage environment.

The International Electrotechnical Commission also has standards (IEC, 1990) to classify environmental conditions which are more elaborate than the above. They define ranges of meteorological, physical and biological environments that may be encountered by products being transported, stored, installed and used, which are useful for equipment specification and for planning tests.

4.2.2.2 **Environmental test programme**

Environmental tests in the laboratory enable rapid testing over a wide range of conditions, and can accelerate certain effects such as those of a marine environment with high atmospheric salt loading. The advantage of environmental tests over field tests is that many tests can be accelerated in a well-equipped laboratory, and equipment may be tested over a wide range of climatic variability. Environmental testing is important; it can give insight into potential problems and generate confidence to go ahead with field tests, but it cannot replace field testing.

An environmental test programme is usually designed around a subset of the following conditions: high temperature, low temperature, temperature shock, temperature cycling, humidity, wind, rain, freezing rain, dust, sunshine (insolation), low pressure, transportation vibration and transportation shock. The ranges, or test limits, of each test are determined by the expected environments (operational, withstanding, outdoor, indoor, transportation, storage) that are expected to be encountered.

The purpose of an environmental test programme document is to establish standard environmental test criteria and corresponding test procedures for the specification, procurement, design and testing of equipment. This document should be based on the expected environmental operating conditions and extremes.

For example, the United States prepared its National Weather Service standard environmental criteria and test procedures (NWS, 1984), based on a study which surveyed and reported the expected operational and extreme ranges of the various weather elements in the United States operational area, and presented proposed test criteria (NWS, 1980). These criteria and procedures consist of three parts:

(a) Environmental test criteria and test limits for outdoor, indoor, and transportation/storage environments;
(b) Test procedures for evaluating equipment against the environmental test criteria;
(c) Rationale providing background information on the various environmental conditions to which equipment may be exposed, their potential effect(s) on the equipment, and the corresponding rationale for the recommended test criteria.

4.2.3 Electrical and electromagnetic interference testing

The prevalence of sensors and automated data collection and processing systems that contain electronic components necessitates in many cases the inclusion in an overall test programme for testing performance in operational electrical environments and under electromagnetic interference.

An electrical/electromagnetic interference test programme document should be prepared. The purpose of the document is to establish standard electrical/electromagnetic interference test criteria and corresponding test procedures and to serve as a uniform guide in the specification of electrical/electromagnetic interference susceptibility requirements for the procurement and design of equipment.

The document should be based on a study that quantifies the expected power line and signal line transient levels and rise times caused by natural phenomena, such as thunderstorms. It should also include testing for expected power variations, both voltage and phase. If the equipment is expected to operate in an airport environment, or other environment with possible electromagnetic radiation interference, this should also be quantified and included in the standard. A purpose of the programme may also be to ensure that the equipment is not an electromagnetic radiation generator. Particular attention should be paid to equipment containing a microprocessor and, therefore, a crystal clock, which is critical for timing functions.

4.2.4 Functional testing

Calibration and environmental testing provide a necessary but not sufficient basis for defining the operational characteristics of a sensor or system, because calibration and laboratory testing cannot completely define how the sensor or system will operate in the field. It is impossible to simulate the synergistic effects of all the changing weather elements on an instrument in all of its required operating environments.

Functional testing is simply testing in the outdoor and natural environment where instruments are expected to operate over a wide variety of meteorological conditions and climatic regimes, and, in the case of surface instruments, over ground surfaces of widely varying albedo. Functional testing is required to determine the adequacy of a sensor or system while it is exposed to wide variations in wind, precipitation, temperature, humidity, and direct, diffuse and reflected solar radiation. Functional testing becomes more important as newer technology sensors, such as those using electro-optic, piezoelectric and capacitive elements, are placed into operational use. The readings from these sensors may be affected by adventitious conditions such as insects, spiders and their webs, and the size distribution of particles in the atmosphere, all of which must be determined by functional tests.

For many applications, comparability must be tested in the field. This is done with side-by-side testing of like and different sensors or systems against a field reference standard. These concepts are presented in Hoehne (1971; 1972; 1977).

Functional testing may be planned and carried out by private laboratories or by the test department of the Meteorological Service or other user organization. For both the procurement and operation of equipment, the educational and skill level of the observers and technicians who will use the system must be considered. Use of the equipment by these staff members should be part of the test programme. The personnel who will install, use, maintain and repair the equipment should evaluate those portions of the sensor or system, including the adequacy of the instructions and manuals that they will use in their job. Their skill level should also be considered when preparing procurement specifications.

4.3 CALIBRATION

4.3.1 The purpose of calibration

Sensor or system calibration is the first step in defining data validity. In general, it involves comparison against a known standard to determine how closely instrument output matches the standard over the expected range of operation. Performing laboratory calibration carries the implicit assumption that the instrument's characteristics are stable enough to retain the calibration in the field. A calibration history over successive calibrations should provide confidence in the instrument's stability.

Specifically, calibration is the set of operations that establish, under specified conditions, the relationship between the values indicated by a measuring instrument or measuring system and the corresponding known values of a measurand, namely the quantity to be measured. It should define a sensor/system's bias or average deviation from the standard against which it is calibrated, its random errors, the range over which the calibration is valid, and the existence of any thresholds or non-linear response regions. It should also define resolution and hysteresis. Hysteresis should be identified by cycling the sensor over its operating range during calibration. The result of a calibration is often expressed as a calibration factor or as a series of calibration factors in the form of a calibration table or calibration curve. The results of a calibration must be recorded in a document called a calibration certificate or a calibration report.

The calibration certificate or report should define any bias that can then be removed through mechanical, electrical or software adjustment. The remaining random error is not repeatable and cannot be removed, but can be statistically defined through a sufficient number of measurement repetitions during calibration.

4.3.2 **Standards**

The calibration of instruments or measurement systems is customarily carried out by comparing them against one or more measurement standards. These standards are classified according to their metrological quality. Their definitions (ISO, 1993) are given in Part I, Chapter 1 and may be summarized as follows:

Primary standard: A standard which has the highest metrological qualities and whose value is accepted without reference to other standards.

Secondary standard: A standard whose value is assigned by comparison with a primary standard.

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

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

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

Working standard: A standard that is used routinely to calibrate or check measuring instruments.

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

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

Primary standards reside within major international or national institutions. Secondary standards often reside in major calibration laboratories and are usually not suitable for field use. Working standards are usually laboratory instruments that have been calibrated against a secondary standard. Working standards that may be used in the field are known as transfer standards. Transfer standard instruments may also be used to compare instruments in a laboratory or in the field.

4.3.3 **Traceability**

Traceability is defined by ISO (1993) as:

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

In meteorology, it is common practice for pressure measurements to be traceable through travelling standards, working standards and secondary standards to national or primary standards, and the accumulated uncertainties therefore are known (except for those that arise in the field, which have to be determined by field testing). Temperature measurements lend themselves to the same practice.

The same principle must be applied to the measurement of any quantity for which measurements of known uncertainty are required.

4.3.4 **Calibration practices**

The calibration of meteorological instruments is normally carried out in a laboratory where appropriate measurement standards and calibration devices are located. They may be national laboratories, private laboratories, or laboratories established within the Meteorological Service or other user organization. A calibration laboratory is responsible for maintaining the necessary qualities of its measurement standards and for keeping records of their traceability. Such laboratories can also issue calibration certificates that should also contain an estimate of the accuracy of calibration. In order to guarantee traceability, the calibration laboratory should be recognized and authorized by the appropriate national authorities.

Manufacturers of meteorological instruments should deliver their quality products, for example, standard barometers or thermometers, with calibration certificates or calibration reports. These documents may or may not be included in the basic price of the instrument, but may be available as options. Calibration certificates given by authorized calibration laboratories may be more expensive than factory certificates. As discussed in the previous section, environmental, functional, and possibly additional calibration testing, should be performed.

Users may also purchase calibration devices or measurement standards for their own laboratories. A good calibration device should always be combined with a proper measurement standard, for example, a liquid bath temperature calibration chamber with a set of certified liquid-in-glass thermometers, and/or certified resistance thermometers. For the example above, further considerations, such as the use of non-conductive silicone fluid, should be applied. Thus, if a temperature-measurement device is mounted on an electronic circuit board, the entire board may be immersed in the bath so that the device can be tested in its operating configuration. Not only must the calibration equipment and standards be of high quality, but the engineers and technicians of a calibration laboratory must be well trained in basic metrology and in the use of available calibration devices and measurement standards.

Once instruments have passed initial calibration and testing and are accepted by the user, a programme of regular calibration checks and calibrations should be instituted. Instruments, such as mercury barometers, are easily subject to breakage when transported to field sites. At distant stations, these instruments should be kept stationary as far as possible, and should be calibrated against more robust travelling standards that can be moved from one station to another by inspectors. Travelling standards must be compared frequently against a working standard or reference standard in the calibration laboratory, and before and after each inspection tour.

Details of laboratory calibration procedures of, for example, barometers, thermometers, hygrometers, anemometers and radiation instruments are given in the relevant chapters of this Guide or in specialized handbooks. These publications also contain information concerning recognized international standard instruments and calibration devices. Calibration procedures for automatic weather stations require particular attention, as discussed in Part II, Chapter 1.

WMO (1989) gives a detailed analysis of the calibration procedures used by several Meteorological Services for the calibration of instruments used to measure temperature, humidity, pressure and wind.

4.4 INTERCOMPARISONS

Intercomparisons of instruments and observing systems, together with agreed quality-control procedures, are essential for the establishment of compatible data sets. All intercomparisons should be planned and carried out carefully in order to maintain an adequate and uniform quality level of measurements of each meteorological variable. Many meteorological quantities cannot be directly compared with metrological standards and hence to absolute references — for example, visibility, cloud-base height and precipitation. For such quantities, intercomparisons are of primary value.

Comparisons or evaluations of instruments and observing systems may be organized and carried out at the following levels:

(a) International comparisons, in which participants from all interested countries may attend in response to a general invitation;
(b) Regional intercomparisons, in which participants from countries of a certain region (for example, WMO Regions) may attend in response to a general invitation;
(c) Multilateral and bilateral intercomparisons, in which participants from two or more countries may agree to attend without a general invitation;
(d) National intercomparisons, within a country.

Because of the importance of international comparability of measurements, WMO, through one of its constituent bodies, from time to time arranges for international and regional comparisons of instruments. Such intercomparisons or evaluations of instruments and observing systems may be very lengthy and expensive. Rules have therefore been established so that coordination will be effective and assured. These rules are reproduced in Annexes 4.A and 4.B.[2] They contain general guidelines and should, when necessary, be supplemented by specific working rules for each intercomparison (see the relevant chapters of this Guide).

Reports of particular WMO international comparisons are referenced in other chapters in this Guide (see, for instance, Part I, Chapters 3, 4, 9, 12, 14 and 15). Annex 4.C provides a list of the international comparisons which have been supported by the Commission for Instruments and Methods of Observation and which have been published in the WMO technical document series.

Reports of comparisons at any level should be made known and available to the meteorological community at large.

---

[2] Recommendations adopted by the Commission for Instruments and Methods of Observation at its eleventh session, through the annex to Recommendation 14 (CIMO-XI) and Annex IX (1994).

ANNEX 4.A

PROCEDURES OF WMO GLOBAL AND REGIONAL INTERCOMPARISONS OF INSTRUMENTS

1. A WMO intercomparison of instruments and methods of observation shall be agreed upon by the WMO constituent body concerned so that it is recognized as a WMO intercomparison.

2. The Executive Council will consider the approval of the intercomparison and its inclusion in the programme and budget of WMO.

3. When there is an urgent need to carry out a specific intercomparison that was not considered at the session of a constituent body, the president of the relevant body may submit a corresponding proposal to the President of WMO for approval.

4. In good time before each intercomparison, the Secretary-General, in cooperation with the president of CIMO and possibly with presidents of other technical commissions or regional associations, or heads of programmes concerned, should make inquiries as to the willingness of one or more Members to act as a host country and as to the interest of Members in participating in the intercomparison.

5. When at least one Member has agreed to act as host country and a reasonable number of Members have expressed their interest in participating, an international organizing committee should be established by the president of CIMO in consultation with the heads of the constituent bodies concerned, if appropriate.

6. Before the intercomparison begins, the organizing committee should agree on its organization, for example, at least on the main objectives, place, date and duration of the intercomparison, conditions for participation, data acquisition, processing and analysis methodology, plans for the publication of results, intercomparison rules, and the responsibilities of the host(s) and the participants.

7. The host should nominate a project leader who will be responsible for the proper conduct of the intercomparison, the data analysis, and the preparation of a final report of the intercomparison as agreed upon by the organizing committee. The project leader will be a member ex officio of the organizing committee.

8. When the organizing committee has decided to carry out the intercomparison at sites in different host countries, each of these countries should designate a site manager. The responsibilities of the site managers and the overall project management will be specified by the organizing committee.

9. The Secretary-General is invited to announce the planned intercomparison to Members as soon as possible after the establishment of the organizing committee. The invitation should include information on the organization and rules of the intercomparison as agreed upon by the organizing committee. Participating Members should observe these rules.

10. All further communication between the host(s) and the participants concerning organizational matters will be handled by the project leader and possibly by the site managers unless other arrangements are specified by the organizing committee.

11. Meetings of the organizing committee during the period of the intercomparison could be arranged, if necessary.

12. After completion of the intercomparison, the organizing committee shall discuss and approve the main results of the data analysis of the intercomparison and shall make proposals for the utilization of the results within the meteorological community.

13. The final report of the intercomparison, prepared by the project leader and approved by the organizing committee, should be published in the WMO Instruments and Observing Methods Report series.

ANNEX 4.B

GUIDELINES FOR ORGANIZING WMO INTERCOMPARISONS OF INSTRUMENTS

1. INTRODUCTION

1.1 These guidelines are complementary to the procedures of WMO global and regional intercomparisons of meteorological instruments. They assume that an international organizing committee has been set up for the intercomparison and provide guidance to the organizing committee for its conduct. In particular, see Part I, Chapter 12, Annex 12.C.

1.2 However, since all intercomparisons differ to some extent from each other, these guidelines should be considered as a generalized checklist of tasks. They should be modified as situations so warrant, keeping in mind the fact that fairness and scientific validity should be the criteria that govern the conduct of WMO intercomparisons and evaluations.

1.3 Final reports of other WMO intercomparisons and the reports of meetings of organizing committees may serve as examples of the conduct of intercomparisons. These are available from the World Weather Watch Department of the WMO Secretariat.

2. OBJECTIVES OF THE INTERCOMPARISON

The organizing committee should examine the achievements to be expected from the intercomparison and identify the particular problems that may be expected. It should prepare a clear and detailed statement of the main objectives of the intercomparison and agree on any criteria to be used in the evaluation of results. The organizing committee should also investigate how best to guarantee the success of the intercomparison, making use of the accumulated experience of former intercomparisons, as appropriate.

3. PLACE, DATE AND DURATION

3.1 The host country should be requested by the Secretariat to provide the organizing committee with a description of the proposed intercomparison site and facilities (location(s), environmental and climatological conditions, major topographic features, and so forth). It should also nominate a project leader.[3]

3.2 The organizing committee should examine the suitability of the proposed site and facilities, propose any necessary changes, and agree on the site and facilities to be used. A full site and environmental description should then be prepared by the project leader. The organizing committee, in consultation with the project leader, should decide on the date for the start and the duration of the intercomparison.

3.3 The project leader should propose a date by which the site and its facilities will be available for the installation of equipment and its connection to the data-acquisition system. The schedule should include a period of time to check and test equipment and to familiarize operators with operational and routine procedures.

4. PARTICIPATION IN THE INTERCOMPARISON

4.1 The organizing committee should consider technical and operational aspects, desirable features and preferences, restrictions, priorities, and descriptions of different instrument types for the intercomparison.

4.2 Normally, only instruments in operational use or instruments that are considered for operational use in the near future by Members should be admitted. It is the responsibility of the participating Members to calibrate their instruments against recognized standards before shipment and to provide appropriate calibration certificates. Participants may be requested to provide two identical instruments of each type in order to achieve more confidence in the data. However, this should not be a condition for participation.

---

[3] When more than one site is involved, site managers shall be appointed, as required. Some tasks of the project leader, as outlined in this annex, shall be delegated to the site managers.

4.3 The organizing committee should draft a detailed questionnaire in order to obtain the required information on each instrument proposed for the intercomparison. The project leader shall provide further details and complete this questionnaire as soon as possible. Participants will be requested to specify very clearly the hardware connections and software characteristics in their reply and to supply adequate documentation (a questionnaire checklist is available from the WMO Secretariat).

4.4 The chairperson of the organizing committee should then request:

(a) The Secretary-General to invite officially Members (who have expressed an interest) to participate in the intercomparison. The invitation shall include all necessary information on the rules of the intercomparison as prepared by the organizing committee and the project leader;
(b) The project leader to handle all further contact with participants.

5. DATA ACQUISITION

5.1 Equipment set-up

5.1.1 The organizing committee should evaluate a proposed layout of the instrument installation prepared by the project leader and agree on a layout of instruments for the intercomparison. Special attention should be paid to fair and proper siting and exposure of instruments, taking into account criteria and standards of WMO and other international organizations. The adopted siting and exposure criteria shall be documented.

5.1.2 Specific requests made by participants for equipment installation should be considered and approved, if acceptable, by the project leader on behalf of the organizing committee.

5.2 Standards and references

The host country should make every effort to include at least one reference instrument in the intercomparison. The calibration of this instrument should be traceable to national or international standards. A description and specification of the standard should be provided to the organizing committee. If no recognized standard or reference exists for the variable(s) to be measured, the organizing committee should agree on a method to determine a reference for the intercomparison.

5.3 Related observations and measurements

The organizing committee should agree on a list of meteorological and environmental variables that should be measured or observed at the intercomparison site during the whole intercomparison period. It should prepare a measuring programme for these and request the host country to execute this programme. The results of this programme should be recorded in a format suitable for the intercomparison analysis.

5.4 Data-acquisition system

5.4.1 Normally the host country should provide the necessary data-acquisition system capable of recording the required analogue, pulse and digital (serial and parallel) signals from all participating instruments. A description and a block diagram of the full measuring chain should be provided by the host country to the organizing committee. The organizing committee, in consultation with the project leader, should decide whether analogue chart records and visual readings from displays will be accepted in the intercomparison for analysis purposes or only for checking the operation.

5.4.2 The data-acquisition system hardware and software should be well tested before the comparison is started and measures should be taken to prevent gaps in the data record during the intercomparison period.

5.5 Data-acquisition methodology

The organizing committee should agree on appropriate data-acquisition procedures, such as frequency of measurement, data sampling, averaging, data reduction, data formats, real-time quality control, and so on. When data reports have to be made by participants during the time of the intercomparison or when data are available as chart records or visual observations, the organizing committee should agree on the responsibility for checking these data, on the period within which the data should be submitted to the project leader, and on the formats and media that would allow storage of these data in the database of the host. When possible, direct comparisons should be made against the reference instrument.

5.6 Schedule of the intercomparison

The organizing committee should agree on an outline of a time schedule for the intercomparison, including normal and specific tasks, and prepare a time chart. Details should be further worked out by the project leader and the project staff.

6. DATA PROCESSING AND ANALYSIS

6.1 Database and data availability

6.1.1 All essential data of the intercomparison, including related meteorological and environmental data, should be stored in a database for further analysis under the supervision of the project leader. The organizing committee, in collaboration with the project leader, should propose a common format for all data, including those reported by participants during the intercomparison. The organizing committee should agree on near-real-time monitoring and quality-control checks to ensure a valid database.

6.1.2 After completion of the intercomparison, the host country should, on request, provide each participating Member with a data set from its submitted instrument(s). This set should also contain related meteorological, environmental and reference data.

6.2 Data analysis

6.2.1 The organizing committee should propose a framework for data analysis and processing and for the presentation of results. It should agree on data conversion, calibration and correction algorithms, and prepare a list of terms, definitions, abbreviations and relationships (where these differ from commonly accepted and documented practice). It should elaborate and prepare a comprehensive description of statistical methods to be used that correspond to the intercomparison objectives.

6.2.2 Whenever a direct, time-synchronized, one-on-one comparison would be inappropriate (for example, in the case of spatial separation of the instruments under test), methods of analysis based on statistical distributions should be considered. Where no reference instrument exists (as for cloud base, meteorological optical range, and so on), instruments should be compared against a relative reference selected from the instruments under test, based on median or modal values, with care being taken to exclude unrepresentative values from the selected subset of data.

6.2.3 Whenever a second intercomparison is established some time after the first, or in a subsequent phase of an ongoing intercomparison, the methods of analysis and the presentation should include those used in the original study. This should not preclude the addition of new methods.

6.2.4 Normally the project leader should be responsible for the data-processing and analysis. The project leader should, as early as possible, verify the appropriateness of the selected analysis procedures and, as necessary, prepare interim reports for comment by the members of the organizing committee. Changes should be considered, as necessary, on the basis of these reviews.

6.2.5 After completion of the intercomparison, the organizing committee should review the results and analysis prepared by the project leader. It should pay special attention to recommendations for the utilization of the intercomparison results and to the content of the final report.

7. FINAL REPORT OF THE INTERCOMPARISON

7.1 The organizing committee should draft an outline of the final report and request the project leader to prepare a provisional report based on it.

7.2 The final report of the intercomparison should contain, for each instrument, a summary of key performance characteristics and operational factors. Statistical analysis results should be presented in tables and graphs, as appropriate. Time-series plots should be considered for selected periods containing events of particular significance. The host country should be invited to prepare a chapter describing the database and facilities used for data-processing, analysis and storage.

7.3 The organizing committee should agree on the procedures to be followed for approval of the final report, such as:

(a) The draft final report will be prepared by the project leader and submitted to all organizing committee members and, if appropriate, also to participating Members;
(b) Comments and amendments should be sent back to the project leader within a specified time limit, with a copy to the chairperson of the organizing committee;
(c) When there are only minor amendments proposed, the report can be completed by the project leader and sent to the WMO Secretariat for publication;
(d) In the case of major amendments or if serious problems arise that cannot be resolved by

correspondence, an additional meeting of the organizing committee should be considered (the president of CIMO should be informed of this situation immediately).

7.4 The organizing committee may agree that intermediate and final results may be presented only by the project leader and the project staff at technical conferences.

8. RESPONSIBILITIES

8.1 Responsibilities of participants

8.1.1 Participants shall be fully responsible for the transportation of all submitted equipment, all import and export arrangements, and any costs arising from these. Correct import/export procedures shall be followed to ensure that no delays are attributable to this process.

8.1.2 Participants shall generally install and remove any equipment under the supervision of the project leader, unless the host country has agreed to do this.

8.1.3 Each participant shall provide all necessary accessories, mounting hardware, signal and power cables and connectors (compatible with the standards of the host country), spare parts and consumables for its equipment. Participants requiring a special or non-standard power supply shall provide their own converter or adapter. Participants shall provide all detailed instructions and manuals needed for installation, operation, calibration and routine maintenance.

8.2 Host country support

8.2.1 The host country should provide, if asked, the necessary information to participating Members on temporary and permanent (in the case of consumables) import and export procedures. It should assist with the unpacking and installation of the participants' equipment and provide rooms or cabinets to house equipment that requires protection from the weather and for the storage of spare parts, manuals, consumables, and so forth.

8.2.2 A reasonable amount of auxiliary equipment or structures, such as towers, shelters, bases or foundations, should be provided by the host country.

8.2.3 The necessary electrical power for all instruments shall be provided. Participants should be informed of the network voltage and frequency and their stability. The connection of instruments to the data-acquisition system and the power supply will be carried out in collaboration with the participants. The project leader should agree with each participant on the provision, by the participant or the host country, of power and signal cables of adequate length (and with appropriate connectors).

8.2.4 The host country should be responsible for obtaining legal authorization related to measurements in the atmosphere, such as the use of frequencies, the transmission of laser radiation, compliance with civil and aeronautical laws, and so forth. Each participant shall submit the necessary documents at the the request of the project leader.

8.2.5 The host country may provide information on accommodation, travel, local transport, daily logistic support, and so forth.

8.3 Host country servicing

8.3.1 Routine operator servicing by the host country will be performed only for long-term intercomparisons for which absence of participants or their representatives can be justified.

8.3.2 When responsible for operator servicing, the host country should:

(a) Provide normal operator servicing for each instrument, such as cleaning, chart changing, and routine adjustments as specified in the participant's operating instructions;

(b) Check each instrument every day of the intercomparison and inform the nominated contact person representing the participant immediately of any fault that cannot be corrected by routine maintenance;

(c) Do its utmost to carry out routine calibration checks according to the participant's specific instructions.

8.3.3 The project leader should maintain in a log regular records of the performance of all equipment participating in the intercomparison. This log should contain notes on everything at the site that may have an effect on the intercomparison, all events concerning participating equipment, and all events concerning equipment and facilities provided by the host country.

9. RULES DURING THE INTERCOMPARISON

9.1 The project leader shall exercise general control of the intercomparison on behalf of the organizing committee.

9.2 No changes to the equipment hardware or software shall be permitted without the concurrence of the project leader.

9.3 Minor repairs, such as the replacement of fuses, will be allowed with the concurrence of the project leader.

9.4 Calibration checks and equipment servicing by participants, which requires specialist knowledge or specific equipment, will be permitted according to predefined procedures.

9.5 Any problems that arise concerning the participants' equipment shall be addressed to the project leader.

9.6 The project leader may select a period during the intercomparison in which equipment will be operated with extended intervals between normal routine maintenance in order to assess its susceptibility to environmental conditions. The same extended intervals will be applied to all equipment.

ANNEX 4.C

REPORTS OF INTERNATIONAL COMPARISONS CONDUCTED UNDER THE AUSPICES OF THE COMMISSION FOR INSTRUMENTS AND METHODS OF OBSERVATION

Topic	*Instruments and Observing Report No.*	*Title of report*
Pressure	46	*The WMO Automatic Digital Barometer Intercomparison* (de Bilt, Netherlands, 1989–1991), J.P. van der Meulen, WMO/TD-No. 474 (1992).
Humidity	34	*WMO Assmann Aspiration Psychrometer Intercomparison* (Potsdam, German Democratic Republic, 1987), D. Sonntag, WMO/TD-No. 289 (1989).
Humidity	38	*WMO International Hygrometer Intercomparison* (Oslo, Norway, 1989), J. Skaar, K. Hegg, Moe and K.S. Smedstud, WMO/TD-No. 316 (1989).
Wind	62	*WMO Wind Instrument Intercomparison* (Mont Aigoual, France, 1992–1993), P. Gregoire and G. Oualid, WMO/TD-No. 859 (1997).
Precipitation	17	*International Comparison of National Precipitation Gauges with a Reference Pit Gauge* (1984), B. Sevruk and W.R. Hamon, WMO/TD-No. 38 (1984).
Precipitation	67	*WMO Solid Precipitation Measurement Intercomparison – Final Report* (1998), B.E. Goodison, P.Y.T. Louie and D. Yang, WMO/TD-No. 872. (1998).
Radiation[a]	16	*Radiation and Sunshine Duration Measurements: Comparison of Pyranometers and Electronic Sunshine Duration Recorders of RA VI* (Budapest, Hungary, July–December 1984), G. Major, WMO/TD-No. 146 (1986).
Radiation[a]	43	*First WMO Regional Pyrheliometer Comparison of RA II and RA V* (Tokyo, Japan, 23 January–4 February 1989), Y. Sano, WMO/TD-No. 308 (1989).
Radiation[a]	44	*First WMO Regional Pyrheliometer Comparison of RA IV* (Ensenada, Mexico, 20–27 April 1989), I. Galindo, WMO/TD-No. 345 (1989).
Radiation[a]	53	*Segunda Comparación de la OMM de Pirheliómetros Patrones Nacionales AR III* (Buenos Aires, Argentina, 25 November–13 December 1991), M. Ginzburg, WMO/TD-No. 572 (1992).
Radiation[a]	64	*Tercera Comparación Regional de la OMM de Pirheliómetros Patrones Nacionales AR III – Informe Final* (Santiago, Chile, 24 February–7 March 1997), M.V. Muñoz, WMO/TD-No. 861 (1997).
Sunshine duration	16	*Radiation and Sunshine Duration Measurements: Comparison of Pyranometers and Electronic Sunshine Duration – Recorders of RA VI* (Budapest, Hungary, July–December 1984), G. Major, WMO/TD-No. 146 (1986).
Visibility	41	*The First WMO Intercomparison of Visibility Measurements* (United Kingdom, 1988/1989), D.J. Griggs, D.W. Jones, M. Ouldridge and W.R. Sparks, WMO/TD-No. 401 (1990).
Radiosondes	28	*WMO International Radiosonde Comparison, Phase I* (Beaufort Park, United Kingdom, 1984), A.H. Hooper, WMO/TD-No. 174 (1986).

[a] The reports of the WMO International Pyrheliometer Intercomparisons, conducted by the World Radiation Centre at Davos (Switzerland) and carried out at five-yearly intervals, are also distributed by WMO.

Topic	*Instruments and Observing Report No.*	*Title of report*
Radiosondes	29	*WMO International Radiosonde Intercomparison, Phase II* (Wallops Island, United States, 4 February–15 March 1985), F.J. Schmidlin, WMO/TD-No. 312 (1988).
Radiosondes	30	*WMO International Radiosonde Comparison* (United Kingdom, 1984/United States, 1985), J. Nash and F.J. Schmidlin, WMO/TD-No. 195 (1987).
Radiosondes	40	*WMO International Radiosonde Comparison, Phase III* (Dzhambul, USSR, 1989), A. Ivanov, A. Kats, S. Kurnosenko, J. Nash and N. Zaitseva, WMO/TD-No. 451 (1991).
Radiosondes	59	*WMO International Radiosonde Comparison, Phase IV* (Tsukuba, Japan, 15 February–12 March 1993), S. Yagy, A. Mita and N. Inoue, WMO/TD-No. 742 (1996).
Radiosondes	76	*WMO Intercomparison of GPS Radiosondes – Executive Summary* (Alcantâra, Maranhão, Brazil, 20 May–10 June 2001), R.B. da Silveira, G. Fisch, L.A.T. Machado, A.M. Dall'Antonia Jr., L.F. Sapucci, D. Fernandes and J. Nash, WMO/TD-No. 1153 (2003).
Radiosondes	83	*WMO Intercomparison of Radiosonde Systems* (Vacoas, Maurutius, 2–25 February 2005), J. Nash, R. Smout, T. Oakley, B. Pathack and S. Kurnosenko, WMO/TD-No. 1303 (2006).
Cloud-base height	32	*WMO International Ceilometer Intercomparison* (United Kingdom, 1986), D.W. Jones, M. Ouldridge and D.J. Painting, WMO/TD-No. 217 (1988).
Present weather	73	*WMO Intercomparison of Present Weather Sensors/Systems – Final Report* (Canada and France France, 1993–1995), M. Leroy, C. Bellevaux, J.P. Jacob, WMO/TD-No. 887 (1998).

REFERENCES AND FURTHER READING

International Electrotechnical Commission, 1990: *Classification of Environmental Conditions*. IEC 721.

International Organization for Standardization, 1989*a*: *Sampling Procedures for Inspection by Attributes*. – Part I: Sampling plans indexed by acceptable quality level (AQL) for lot-by-lot inspection. ISO 2859-1: 1989.

International Organization for Standardization, 1989*b*: *Sampling Procedures and Charts for Inspection by Variables for Percent Nonconforming*. ISO 3951: 1989.

International Organization for Standardization, 1993: *International Vocabulary of Basic and General Terms in Metrology*. Second edition, ISO Guide 99:1993.

Hoehne, W.E., 1971: *Standarding Functional Tests*. NOAA Technical Memorandum, NWS T&EL-12, United States Department of Commerce, Sterling, Virginia.

Hoehne, W.E., 1972: Standardizng functional tests. *Preprints of the Second Symposium on Meteorological Observations and Instrumentation*, American Meteorological Society, pp. 161–165.

Hoehne, W.E., 1977: *Progress and Results of Functional Testing*. NOAA Technical Memorandum NWS T&EL-15, United States Department of Commerce, Sterling, Virginia.

National Weather Service, 1980: *Natural Environmental Testing Criteria and Recommended Test Methodologies for a Proposed Standard for National Weather Service Equipment*. United States Department of Commerce, Sterling, Virginia.

National Weather Service, 1984: *NWS Standard Environmental Criteria and Test Procedures*. United States Department of Commerce, Sterling, Virginia.

World Meteorological Organization/International Council of Scientific Unions, 1986: *Revised Instruction Manual on Radiation Instruments and Measurements* (C. Fröhlich and J. London, eds). World Climate Research Programme Publications Series No. 7, WMO/TD-No. 149, Geneva.

World Meteorological Organization, 1989: *Analysis of Instrument Calibration Methods Used by Members* (H. Doering). Instruments and Observing Methods Report No. 45, WMO/TD-No. 310, Geneva.

CHAPTER 5

TRAINING OF INSTRUMENT SPECIALISTS

5.1 INTRODUCTION

5.1.1 General

Given that the science and application of meteorology are based on continuous series of measurements using instruments and systems of increasing sophistication, this chapter is concerned with the training of those specialists who deal with the planning, specification, design, installation, calibration, maintenance and application of meteorological measuring instruments and remote-sensing systems. This chapter is aimed at technical managers and trainers and not least at the instrument specialists themselves who want to advance in their profession.

Training skilled personnel is critical to the availability of necessary and appropriate technologies in all countries so that the WMO Global Observing System can produce cost-effective data of uniform good quality and timeliness. However, more than just technical ability with instruments is required. Modern meteorology requires technologists who are also capable as planners and project managers, knowledgeable about telecommunications and data processing, good advocates for effective technical solutions, and skilled in the areas of financial budgets and people management. Thus, for the most able instrument specialists or meteorological instrument systems engineers, training programmes should be broad-based and include personal development and management skills as well as expertise in modern technology.

Regional Training Centres (RTCs) have been established in many countries under the auspices of WMO, and many of them offer training in various aspects of the operation and management of instruments and instrument systems. Regional Traning Centres are listed in the annex. Similarly, Regional Instrument Centres (RICs) have been set up in many places, and some of them can provide training. Their locations and functions are listed in Part I, Chapter 1, Annex 1. A and are discussed briefly in section 5.5.1.2.

5.1.2 Technology transfer

Training is a vital part of the process of technology transfer, which is the developmental process of introducing new technical resources into service to improve quality and reduce operating costs. New resources demand new skills for the introductory process and for ongoing operation and maintenance. This human dimension is more important in capacity building than the technical material.

As meteorology is a global discipline, the technology gap between developed and developing nations is a particular issue for technology transfer. Providing for effective training strategies, programmes and resources which foster self-sustaining technical infrastructures and build human capacity in developing countries is a goal that must be kept constantly in view.

5.1.3 Application to all users of meteorological instruments

This chapter deals with training mainly as an issue for National Hydrometeorological Services. However, the same principles apply to any organizations that take meteorological measurements, whether they train their own staff or expect to recruit suitably qualified personnel. In common with all the observational sciences, the benefits of training to ensure standardized measurement procedures and the most effective use and care of equipment, are self-evident.

5.2 APPROPRIATE TRAINING FOR OPERATIONAL REQUIREMENTS

5.2.1 Theory and practice

Taking measurements using instrument systems depends on physical principles (for example, the thermal expansion of mercury) to sense the atmospheric variables and transduce them into a standardized form that is convenient for the user, for example, a recorded trace on a chart or an electrical signal to input into an automatic weather station. The theoretical basis for understanding the measurement process must also take into account the coupling of the instrument to the quantity being measured (the representation or "exposure") as well as the instrumental and observational errors with which every measurement is fraught. The basic measurement data is then often further processed and coded in more or less complex ways, thus requiring further theoretical understanding, for example, the reduction of atmospheric pressure to mean sea level and upper-air messages derived from a radiosonde flight.

Taking the measurement also depends on practical knowledge and skill in terms of how to install and set up the instrument to take a standardized measurement, how to operate it safely and accurately, and how to carry out any subsequent calculations or coding processes with minimal error.

Thus, theoretical and practical matters are closely related in achieving measurement data of known quality, and the personnel concerned in the operation and management of the instrument systems need theoretical understanding and practical skills which are appropriate to the complexity and significance of their work. The engineers who design or maintain complex instrumentation systems require a particularly high order of theoretical and practical training.

5.2.2 Matching skills to the tasks

Organizations need to ensure that the qualifications, skills and numbers of their personnel or other contractors (and thus training) are well matched to the range of tasks to be performed. For example, the training needed to read air temperature in a Stevenson screen is at the lower end of the range of necessary skills, while theoretical and practical training at a much higher level is plainly necessary in order to specify, install, operate and maintain automatic weather stations, meteorological satellite receivers and radars.

Therefore, it is useful to apply a classification scheme for the levels of qualification for operational requirements, employment, and training purposes. The national grades of qualification in technical education applicable in a particular country will be important benchmarks. To help the international community achieve uniform quality in their meteorological data acquisition and processing, WMO recommends the use of its own classification of personnel with the accompanying duties that they should be expected to carry out competently.

5.2.3 WMO classification of personnel

The WMO classification scheme[1] identifies two broad categories of personnel: graduate professionals and technicians (WMO, 2002*a*). For meteorological and hydrological personnel, these categories are designated as follows: meteorologist and meteorological technician, and hydrologist and hydrological technician, respectively. The recommended syllabus for each class includes a substantial component on instruments and methods of observation related to the education, training and duties expected at that level. The WMO classification of personnel also sets guidelines for the work content, qualifications and skill levels required for instrument specialists. Section 7.3 of WMO (2002*a*) includes an example of competency requirements, while WMO (2002*b*) offers detailed syllabus examples for the initial training and specialization of meteorological personnel. These guidelines enable syllabi and training courses to be properly designed and interpreted; they also assist in the definition of skill deficits and aid the development of balanced national technical skill resources.

5.3 SOME GENERAL PRINCIPLES FOR TRAINING

5.3.1 Management policy issues

5.3.1.1 A personnel plan

It is important that National Meteorological Services have a personnel plan that includes instrument specialists, recognizing their value in the planning, development and maintenance of adequate and cost-effective weather observing programmes. The plan would show all specialist instrument personnel at graded levels (WMO, 2002*a*) of qualification. Skill deficits should be identified and provision made for recruitment and training.

5.3.1.2 Staff retention

Every effort should be made to retain scarce instrumentation technical skills by providing a work environment that is technically challenging, has opportunities for career advancement, and has salaries comparable with those of other technical skills, both within and outside the Meteorological Service.

5.3.1.3 Personnel development

Training should be an integral part of the personnel plan. The introduction of new technology and re-equipment imply new skill requirements. New recruits will need training appropriate to their previous experience, and skill deficits can also be made up by enhancing the skills of other staff. This training also provides the path for career progression. It is helpful if each staff member has a career profile showing training, qualifications and career

---

[1] Classification scheme approved by the WMO Executive Council at its fiftieth session (1998), and endorsed by the World Meteorological Congress at its thirteenth session (1999).

progression, maintained by the training department, in order to plan personnel development in an orderly manner.

5.3.1.4 Balanced training

National training programmes should aim at a balance of skills over all specialist classes giving due attention to the training, supplementation and refresher phases of training, and which result in a self-sustaining technical infrastructure.

5.3.2 Aims and objectives for training programmes

In order to achieve maximum benefits from training it is essential to have clear aims and specific objectives on which to base training plans, syllabi and expenditure. The following strategic aims and objectives for the training of instrument specialists may be considered.

5.3.2.1 For managers

Management aims in training instrument specialists should be, among others:

(a) To improve and maintain the quality of information in all meteorological observing programmes;
(b) To enable National Meteorological and Hydrological Services (NMHSs) to become self-reliant in the knowledge and skills required for the effective planning, implementation and operation of meteorological data-acquisition programmes, and to enable them to develop maintenance services ensuring maximum reliability, accuracy and economy from instrumentation systems;
(c) To realize fully the value of capital invested in instrumentation systems over their optimum economic life.

5.3.2.2 For trainers

The design of training courses should aim:

(a) To provide balanced programmes of training which meet the defined needs of the countries within each region for skills at graded levels;
(b) To provide effective knowledge transfer and skill enhancement in National Meteorological Services by using appropriately qualified tutors, good training aids and facilities, and effective learning methods;
(c) To provide for monitoring the effectiveness of training by appropriate assessment and reporting procedures;
(d) To provide training at a minimum necessary cost.

5.3.2.3 For trainers and instrument specialists

The general objective of training is to equip instrument specialists and engineers (at graded levels of training and experience):

(a) To appreciate the use, value and desirable accuracy of all instrumental measurements;
(b) To understand and apply the principles of siting instrument enclosures and instruments so that representative, homogeneous and compatible data sets are produced;
(c) To acquire the knowledge and skill to carry out installations, adjustments and repairs and to provide a maintenance service ensuring maximum reliability, accuracy and economy from meteorological instruments and systems;
(d) To be able to diagnose faults logically and quickly from observed symptoms and trace and rectify systematically their causes;
(e) To understand the sources of error in measurements and be competent in the handling of instrument standards and calibration procedures in order to minimize systematic errors;
(f) To keep abreast of new technologies and their appropriate application and acquire new knowledge and skills by means of special and refresher courses;
(g) To plan and design data-acquisition networks, and manage budgets and technical staff;
(h) To manage projects involving significant financial, equipment and staff resources and technical complexity;
(i) To modify, improve, design and make instruments for specific purposes;
(j) To design and apply computer and telecommunications systems and software, control measurements and process raw instrumental data into derived forms and transmit coded messages.

5.3.3 Training for quality

Meteorological data acquisition is a complex and costly activity involving human and material resources, communication and computation. It is necessary to maximize the benefit of the information derived while minimizing the financial and human resources required in this endeavour.

The aim of quality data acquisition is to maintain the flow of representative, accurate and timely instrumental data into the national meteorological processing centres at the least cost. Through every stage of technical training, a broad appreciation of how all staff can affect the quality of the end product should be encouraged. The discipline of total quality management (Walton, 1986, and Imai, 1986) considers the whole measurement environment (applications, procedures, instruments and personnel) in so far as each of its elements may affect quality. In total quality management, the data-acquisition activity is studied as a system or series of processes. Critical elements of each process, for example, time delay, are measured and the variation in the process is defined statistically. Problem-solving tools are used by a small team of people who understand the process, to reduce process variation and thereby improve quality. Processes are continuously refined by incremental improvement.

WMO (1990) provides a checklist of factors under the following headings:

(a) Personnel recruitment and training;
(b) Specification, design and development;
(c) Instrument installation;
(d) Equipment maintenance;
(e) Instrument calibration.

All of the above influence data quality from the instrument expert's point of view. The checklist can be used by managers to examine areas over which they have control to identify points of weakness, by training staff within courses on total quality management concepts, and by individuals to help them be aware of areas where their knowledge and skill should make a valuable contribution to overall data quality.

The International Organization for Standardization provides for formal quality systems, defined by the ISO 9000 group of specifications (ISO, 1994*a*; 1994*b*), under which organizations may be certified by external auditors for the quality of their production processes and services to clients. These quality systems depend heavily on training in quality management techniques.

5.3.4 How people learn

5.3.4.1 The learning environment

Learning is a process that is very personal to the individual, depending on a person's needs and interests. People are motivated to learn when there is the prospect of some reward, for example, a salary increase. Nonetheless, job satisfaction, involvement, personal fulfilment, having some sense of power or influence, and the affirmation of peers and superiors are also strong motivators. These rewards come through enhanced work performance and relationships with others on the job.

Learning is an active process in which the student reacts to the training environment and activity. A change of behaviour occurs as the student is involved mentally, physically and emotionally. Too much mental or emotional stress during learning time will be counterproductive.

Trainers and managers should attempt to stimulate and encourage learning by creating a conducive physical and psychological climate and by providing appropriate experiences and methods that promote learning. Students should feel at ease and be comfortable in the learning environment, which should not provide distractions. The "psychological climate" can be affected by the student's motivation, the manner and vocabulary of the tutor, the affirmation of previously-acquired knowledge, avoiding embarrassment and ridicule, establishing an atmosphere of trust, and the selection of teaching methods.

5.3.4.2 Important principles

Important principles for training include the following:

(a) *Readiness:* Learning will take place more quickly if the student is ready, interested and wants to learn;
(b) *Objectives:* The objectives of the training (including performance standards) should be clear to those responsible and those involved;
(c) *Involvement:* Learning is more effective if students actively work out solutions and do things for themselves, rather than being passively supplied with answers or merely shown a skill;
(d) *Association:* Learning should be related to past experiences, noting similarities and differences;
(e) *Learning rate:* The rate of training should equal the rate at which an individual can learn (confirmed by testing), with learning distributed over several short sessions rather than one long session being more likely to be retained;
(f) *Reinforcement:* Useful exercises and repetition will help instil new learning;
(g) *Intensity:* Intense, vivid or dramatic experiences capture the imagination and make more impact;
(h) *Effectiveness:* Experiences which are satisfying are better for learning than those which are embarrassing or annoying. Approval encourages learning;

(i) *Support:* The trainee's supervisor must be fully supportive of the training and must be able to maintain and reinforce it;
(j) *Planning and evaluation:* Training should be planned, carried out and evaluated systematically, in the context of organizational needs.

5.3.4.3 Varying the methods

People in a group will learn at different speeds. Some training methods (see section 5.4) will suit some individuals better than others and will be more effective under different circumstances. Using a variety of training methods and resources will help the group learn more rapidly.

Research (Moss, 1987) shows that, through the senses, our retention of learning occurs from the following:

(a)	Sight	(83 per cent);
(b)	Hearing	(11 per cent);
(c)	Other senses	(6 per cent).

However, we learn best by actually performing the task. Methods or training media in general order of decreasing effectiveness are:
(a) Real experience;
(b) Simulated practical experience;
(c) Demonstrations and discussions;
(d) Physical models and text;
(e) Film, video and computer animation;
(f) Graphs, diagrams and photographs;
(g) Written text;
(h) Lectures.

These methods may, of course, be used in combination. A good lecture may include some of the other methods.

Traditional educational methods rely heavily on the spoken and written word, whereas evidence shows that visual and hands-on experience are far more powerful.

Training for instrument specialists can take advantage of the widest range of methods and media. The theoretical aspects of measurement and instrument design are taught by lectures based on text and formulas and supported by graphs and diagrams. A working knowledge of the instrument system for operation, maintenance and calibration can be gained by the use of photographs with text, films or videos showing manual adjustments, models which may be disassembled, demonstrations, and ultimately practical experience in operating systems. Unsafe practices or modes of use may be simulated.

5.3.5 Personal skills development

A meteorological instrument systems engineering group needs people who are not only technically capable, but who are broadly educated and are able to speak and write well. Good personal communication skills are necessary to support and justify technical programmes and particularly in management positions. Skilled technologists should receive training so that they can play a wider role in the decisions that affect the development of their Meteorological Service.

There is a tendency for staff who are numerate and have practical, manual ability to be less able with verbal and written linguistic skills. In the annual personal performance review of their staff, managers should identify any opportunities for staff to enhance their personal skills by taking special courses, for example, in public speaking, negotiation, letter and report writing or assertiveness training. Some staff may need assistance in learning a second language in order to further their training.

5.3.6 Management training

Good management skills are an important component of engineering activity. These skills involve time management; staff motivation, supervision and performance assessment (including a training dimension); project management (estimation of resources, budgets, time, staff and materials, and scheduling); problem solving; quality management; and good verbal and written communication skills. Instrument specialists with leadership aptitude should be identified for management training at an appropriate time in their careers.

Today's manager may have access to a personal computer and be adept in the use of office and engineering software packages to be used, for example, for word processing, spreadsheets, databases, statistical analysis with graphics, engineering drawing, flow charting, and project management. Training in the use of these tools can add greatly to personal productivity.

5.3.7 A lifelong occupation

5.3.7.1 Three training phases

Throughout their working lives, instrument specialists should expect to be engaged in repeated cycles of personal training, both through structured study and informal on-the-job training or self-study. Three phases of training can be recognized as follows:

(a) A developmental, training phase when the trainee acquires general theory and practice at graded levels;
(b) A supplementation phase where the training is enhanced by learning about specific techniques and equipment;
(c) A refresher phase where some years after formal training the specialist needs refresher training and updates on current techniques and equipment.

5.3.7.2 Training

For instrument specialists, the training phase of technical education and training usually occurs partly in an external technical institute and partly in the training establishment of the NMHS where a basic course in meteorological instruments is taken. Note that technical or engineering education may extend over both WMO class levels.

5.3.7.3 Specialist training

The supplementation phase will occur over a few years as the specialist takes courses on special systems, for example, automatic weather stations, or radar, or on disciplines like computer software or management skills. Increasing use will be made of external training resources, including WMO-sponsored training opportunities.

5.3.7.4 Refresher training

As the instrument specialist's career progresses there will be a need for periodic refresher courses to cover advances in instrumentation and technology, as well as other supplementary courses.

There is an implied progression in these phases. Each training course will assume that students have some prerequisite training on which to build.

5.4 THE TRAINING PROCESS

5.4.1 The role of the trainer

Most instrument specialists find themselves in the important and satisfying role of trainer from time to time and for some it will become their full-time work, with its own field of expertise. All trainers need an appreciation of the attributes of a good trainer.

A good trainer is concerned with quality results, is highly knowledgeable in specified fields, and has good communication skills. He or she will have empathy with students, and will be patient and tolerant, ready to give encouragement and praise, flexible and imaginative, and practised in a variety of training techniques.

Good trainers will set clear objectives and plan and prepare training sessions well. They will maintain good records of training prescriptions, syllabi, course notes, courses held and the results, and of budgets and expenditures. They will seek honest feedback on their performance and be ready to modify their approach. They will also expect to be always learning.

5.4.2 Task analysis

The instrument specialist must be trained to carry out many repetitive or complex tasks for the installation, maintenance and calibration of instruments, and sometimes for their manufacture. A task analysis form may be used to define the way in which the job is to be done, and could be used by the tutor in training and then as a checklist by the trainee. First, the objective of the job and the required standard of performance is written down. The job is broken down into logical steps or stages of a convenient size. The form might consist of a table whose columns are headed, for example with: steps, methods, measures, and reasons:
(a) Steps (what must be done): These are numbered and consist of a brief description of each step of the task, beginning with an active verb;
(b) Methods (how it is to be done): An indication of the method and equipment to be used or the skill required;
(c) Measures (the standard required): Includes a qualitative statement, reference to a specification clause, test, or actual measure;
(d) Reasons (why it must be done): A brief explanation of the purpose of each step.

A flow chart would be a good visual means of relating the steps to the whole task, particularly when the order of the steps is important or if there are branches in the procedure.

5.4.3 Planning the training session

The training process consists of four stages, as shown in the opposite figure:
(a) Planning:
    (i) Review the training objectives, established by the employing organization or standards-setting body (for example, WMO);
    (ii) Analyse the features of the body of knowledge, task or skill that is the subject of the session;

  - (iii) Review the characteristics of the students: qualifications, work experience, language ability, specific problems;
  - (iv) Assess the required level of training (Which students may need special attention?);
  - (v) Determine the objectives for the session (What results are required? How can they be measured?);

- (b) Preparation:
  - (i) Select course content: Assemble information, organize it in a logical sequence;
  - (ii) Determine training methods and media: appropriate to the topic, so as to create and maintain interest (see section 5.4.5);
  - (iii) Prepare a session plan: Set out the detailed plan with the time of each activity;
  - (iv) Plan evaluation: What information is required and how is it to be collected? Select a method and prepare the questions or assignment;

- (c) Presentation:
  - (i) Carry out training, using the session plan;
  - (ii) Encourage active learning and participation;
  - (iii) Use a variety of methods;
  - (iv) Use demonstrations and visual aids;

- (d) Evaluation:
  - (i) Carry out the planned evaluation with respect to the objectives;
  - (ii) Summarize results;
  - (iii) Review the training session for effectiveness in light of the evaluation;
  - (iv) Consider improvements in content and presentation;
  - (v) Write conclusions;
  - (vi) Apply feedback to the next planning session.

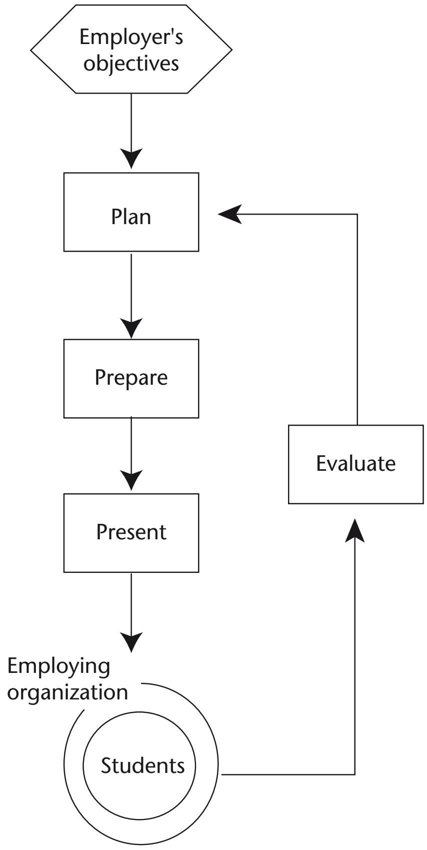


Figure 5.2. Stages in the training process

All training will be more effective if these stages are worked through carefully and systematically.

5.4.4 Effectiveness of training

5.4.4.1 Targeted training

With the limited resources available for training, real effort should be devoted to maximizing the effectiveness of training. Training courses and resources should be dedicated to optimizing the benefits of training the right personnel at the most useful time. For example, too little training may be a waste of resources, sending management staff to a course for maintenance technicians would be inappropriate, and it is pointless to train people 12 months before they have access to new technology.

Training opportunities and methods should be selected to best suit knowledge and skills requirements and trainees, bearing in mind their educational and national backgrounds. To ensure maximum effectiveness, training should be evaluated.

5.4.4.2 Evaluating the training

Evaluation is a process of obtaining certain information and providing it to those who can influence future training performance. Several approaches to evaluating training may be applied, depending on who needs the information among the following:

- (a) WMO, which is concerned with improving the quality of data collected in the Global Observing System. It generates training programmes, establishes funds and uses the services of experts primarily to improve the skill base in developing countries;
- (b) The National Meteorological Service, which which needs quality weather data and is concerned with the overall capability of the division that performs data acquisition and particular instrumentation tasks within

certain staff number constraints. It is interested in the budget and cost-benefit of training programmes;

(c) The training department or Regional Training Centre, which is concerned with establishing training programmes to meet specified objectives within an agreed budget. Its trainers need to know how effective their methods are in meeting these objectives and how they can be improved;

(d) Engineering managers, who are concerned with having the work skills to accomplish their area of responsibility to the required standard and without wasting time or materials;

(e) Trainees, who are concerned with the rewards and job satisfaction that come with increased competence. They will want a training course to meet their needs and expectations.

Thus, the effectiveness of training should be evaluated at several levels. National and Regional Training Centres might evaluate their programmes annually and triennially, comparing the number of trainees in different courses and pass levels against budgets and the objectives which have been set at the start of each period. Trainers will need to evaluate the relevance and effectiveness of the content and presentation of their courses.

5.4.4.3 Types of evaluation

Types of evaluation include the following:

(a) A training report, which does not attempt to measure effectiveness. Instead, it is a factual statement of, for example, the type and the number of courses offered, dates and durations, the number of trainees trained and qualifying, and the total cost of training. In some situations, a report is required on the assessed capability of the student;

(b) Reaction evaluation, which measures the reaction of the trainees to the training programme. It may take the form of a written questionnaire through which trainees score, at the end of the course, their opinions about relevance, content, methods, training aids, presentation and administration. As such, this method cannot improve the training that they receive. Therefore, every training course should have regular opportunities for review and student feedback through group discussion. This enables the trainer to detect any problems with the training or any individual's needs and to take appropriate action;

(c) Learning evaluation, which measures the trainee's new knowledge and skills, which are best compared against a pre-training test. Various forms of written test (essay, short answer questions, true or false questions, multiple-choice questions, drawing a diagram or flow chart) can be devised to test a trainee's knowledge. Trainees may usefully test and score their own knowledge. Skills are best tested by a set practical assignment or by observation during on-the-job training (WMO, 1990). A checklist of required actions and skills (an observation form) for the task may be used by the assessor;

(d) Performance evaluation, which measures how the trainee's performance on the job has changed after some time, in response to training, which is best compared with a pre-training test. This evaluation may be carried out by the employer at least six weeks after training, using an observation form, for example. The training institution may also make an assessment by sending questionnaires to both the employer and the trainee;

(e) Impact evaluation, which measures the effectiveness of training by determining the change in an organization or work group. This evaluation may require planning and the collection of baseline data before and after the specific training. Some measures might be: bad data and the number of data elements missing in meteorological reports, the time taken to perform installations, and the cost of installations.

5.4.4.4 Training for trainers

Trainers also require training to keep abreast of technological advances, to learn about new teaching techniques and media, and to catch a fresh vision of their work. There should be provision in their NMHS's annual budget to allow the NMHS's training staff to take training opportunities, probably in rotation.

Some options are: personal study; short courses (including teaching skills) run by technical institutes; time out for study for higher qualifications; visits to the factories of meteorological equipment manufacturers; visits and secondments to other NMHS and RICs; and attendance at WMO and other training and technical conferences.

5.4.5 Training methods and media

The following list, arranged in alphabetical order, contains only brief notes to serve as a reminder or to suggest possibilities for training methods (more details may be found in many other sources, such as Moss (1987) and Craig (1987)):

(a) Case study:
  (i) A particular real-life problem or development project is set up for study by individuals, or often a team;
  (ii) The presentation of the results could involve formal documentation as would be expected in a real situation;

(b) Classroom lecture:
  (i) This is most suitable for developing an understanding of information which is best mediated in spoken and written form: basic knowledge, theoretical ideas, calculations, procedures;
  (ii) Visual media and selected printed handout material are very useful additions;
  (iii) There should be adequate time for questions and discussion;
  (iv) Lectures tend to be excessively passive;

(c) Computer-assisted instruction:
  (i) This uses the capability of the personal computer to store large amounts of text and images, organized by the computer program into learning sequences, often with some element of interactive choice by the student through menu lists and screen selection buttons;
  (ii) The logical conditions and branching and looping structures of the program simulate the learning processes of selecting a topic for study based on the student's needs, presenting information, testing for understanding with optional answers and then directing revision until the correct answer is obtained;
  (iii) Some computer languages, for example, ToolBook for the IBM personal computer and HyperCard for the Macintosh, are designed specifically for authoring and presenting interactive training courses in what are known as "hypermedia";
  (iv) Modern systems use colour graphic screens and may include diagrams, still pictures and short moving sequences, while a graphical user interface is used to improve the interactive communication between the student and the program;
  (v) Entire meteorological instrument systems, for example, for upper-air sounding, may be simulated on the computer;
  (vi) Elaborate systems may include a laser video disc or DVD player or CD-ROM cartridge on which large amounts of text and moving image sequences are permanently stored;
  (vii)The software development and capital cost of computer-assisted instruction systems range from modest to very great; they are beginning to replace multimedia and video tape training aids;

(d) Correspondence courses:
  (i) The conventional course consists of lessons with exercises or assignments which are mailed to the student at intervals;
  (ii) The tutor marks the assignments and returns them to the student with the next lesson;
  (iii) Sometimes it is possible for students to discuss difficulties with their tutor by telephone;
  (iv) Some courses may include audio or video tapes, or computer disks, provided that the student has access to the necessary equipment;
  (v) At the end of the course an examination may be held at the training centre;

(e) Demonstrations:
  (i) The tutor demonstrates techniques in a laboratory or working situation;
  (ii) This is necessary for the initial teaching of manual maintenance and calibration procedures;
  (iii) Students must have an opportunity to try the procedures themselves and ask questions;

(f) Distance learning:
  (i) Students follow a training course, which is usually part-time, in their own locality and at times that suit their work commitments, remote from the training centre and their tutor;
  (ii) Study may be on an individual or group basis;
  (iii) Some institutions specialize in distance-learning capability;
  (iv) Distance learning is represented in this section by correspondence courses, television lectures and distance learning with telecommunications;

(g) Distance learning with telecommunications:
  (i) A class of students is linked by special telephone equipment to a remote tutor. They study from a printed text. Students each have a microphone which enables them to enter into discussions and engage in question and answer dialogue. Any reliable communications medium could be

used, including satellite, but obviously communications costs will be an issue;
  - (ii) In more elaborate and costly systems, all students have computers that are linked to each other and to the remote tutor's computer via a network; or the tutor teaches from a special kind of television studio and appears on a television monitor in the remote classroom, which also has a camera and microphones so that the tutor can see and hear the students;

(h) Exercises and assignments:
  - (i) These often follow a lecture or demonstration;
  - (ii) They are necessary so that students actively assimilate and use their new knowledge;
  - (iii) An assignment may involve research or be a practical task;

(i) Exhibits:
  - (i) These are prepared display material and models which students can examine;
  - (ii) They provide a useful overview when the real situation is complex or remote;

(j) Field studies and visits:
  - (i) Trainees carry out observing practices and study instrument systems in the field environment, most usefully during installation, maintenance or calibration;
  - (ii) Visits to meteorological equipment manufacturers and other Meteorological Services will expand the technical awareness of specialists;

(k) Group discussion/problem solving:
  - (i) The class is divided into small groups of four to six persons;
  - (ii) The group leader should ensure that all students are encouraged to contribute;
  - (iii) A scribe or recorder notes ideas on a board in full view of the group;
  - (iv) In a brainstorming session, all ideas are accepted in the first round without criticism, then the group explores each idea in detail and ranks its usefulness;

(l) Job rotation/secondment:
  - (i) According to a timetable, the student is assigned to a variety of tasks with different responsibilities often under different supervisors or trainers in order to develop comprehensive work experience;
  - (ii) Students may be seconded for a fixed term to another department, manufacturing company or another Meteorological Service in order to gain work experience that cannot be obtained in their own department or Service;
  - (iii) Students seconded internationally should be very capable and are usually supported by bilateral agreements or scholarships;

(m) Multimedia programmes:
  - (i) These include projection transparencies, video tapes and computer DVDs and CD-ROMs;
  - (ii) They require access to costly equipment which must be compatible with the media;
  - (iii) They may be used for class or individual study;
  - (iv) The programmes should include exercises, questions and discussion topics;
  - (v) Limited material is available for meteorological instrumentation;

(n) One-to-one coaching:
  - (i) The tutor works alongside one student who needs training in a specific skill;
  - (ii) This method may be useful for both remedial and advanced training;

(o) On-the-job training:
  - (i) This is an essential component of the training process and is when the trainee learns to apply the formally acquired skills in the wide variety of tasks and problems which confront the specialist. All skills are learnt best by exercising them;
  - (ii) Certain training activities may be best conducted in the on-the-job mode, following necessary explanations and cautions. These include all skills requiring a high level of manipulative ability and for which it is difficult or costly to reproduce the equipment or conditions in the laboratory or workshop. Examples of this are the installation of equipment, certain maintenance operations and complex calibrations;
  - (iii) This type of training uses available personnel and equipment resources and does not require travel, special training staff or accommodation, and is specific to local needs. It is particularly relevant where practical training far outweighs theoretical study, such as for training technicians;
  - (iv) The dangers are that on-the-job training may be used by default as the "natural" training method in cases where more structured training with a sound

theoretical component is required to produce fully rounded specialists; that supervisors with indifferent abilities may be used; that training may be too narrow in scope and have significant gaps in skills or knowledge; and that the effectiveness of training may not be objectively measured;

   (v) The elements necessary for successful on-the-job training are as follows:
      a. A training plan that defines the skills to be acquired;
      b. Work content covering the required field;
      c. A work supervisor who is a good trainer skilled in the topic, has a good teaching style and is patient and encouraging;
      d. Adequate theoretical understanding to support the practical training;
      e. A work diary for the trainee to record the knowledge acquired and skills mastered;
      f. Progress reviews conducted at intervals by the training supervisor;
      g. An objective measure of successfully acquired skills (by observation or tests);

(p) Participative training:
   (i) This gives students active ownership of the learning process and enables knowledge and experience to be shared;
   (ii) Students are grouped in teams or syndicates and elect their own leaders;
   (iii) This is used for generating ideas, solving problems, making plans, developing projects, and providing leadership training;

(q) Peer-assisted learning:
   (i) This depends on prior common study and preparation;
   (ii) In small groups, students take it in turns to be the teacher, while the other students learn and ask questions;

(r) Programmed learning:
   (i) This is useful for students who are not close to tutors or training institutions;
   (ii) Students work individually at their own pace using structured prepared text, multimedia or computer-based courses;
   (iii) Each stage of the course provides self-testing and revision before moving on to the next topic;
   (iv) Training materials are expensive to produce and course options may be limited.

Good teaching is of greater value than expensive training aids.

5.4.6 Television lectures

Some teaching institutions which provide predominantly extramural courses broadcast lectures to their correspondence students over a special television channel or at certain times on a commercial channel.

5.4.7 Video programmes

Video programmes offer a good training tool because of the following:

(a) They provide a good medium for recording and repeatedly demonstrating procedures when access to the instrument system and a skilled tutor is limited;
(b) The programme may include pauses for questions to be discussed;
(c) A video programme can be optimized by combining it with supplementary written texts and group discussions;
(d) Although professionally made videos are expensive and there is limited material available on meteorological instruments, amateurs can make useful technical videos for local use with modest equipment costs, particularly with careful planning and if a sound track is added subsequently.

5.5 RESOURCES FOR TRAINING

Other than the media resources suggested in the previous section, trainers and managers should be aware of the sources of information and guidance available to them; the external training opportunities which are available; the training institutions which can complement their own work; and, not least, the financial resources which support all training activities.

5.5.1 Training institutions

5.5.1.1 National education and training institutions

In general, NMHSs will be unable to provide the full range of technical education and training required by their instrument specialists, and so will have varying degrees of dependence on external educational institutions for training, supplementary and refresher training in advanced technology. Meteorological engineering managers will need to be conversant with the curricula offered by their national institutions so that they can advise their staff on suitable education and training courses of. WMO (2002*a*; 2002*b*) give guidance on the syllabi necessary for the different classes of instrument specialists.

When instrument specialists are recruited from outside the NMHS to take advantage of well-developed engineering skills, it is desirable that they have qualifications from a recognized national institution. They will then require further training in meteorology and its specific measurement techniques and instrumentation.

5.5.1.2 The role of WMO Regional Instrument Centres in training

On the recommendation of CIMO,[2] several WMO regional associations set up RICs to maintain standards and provide advice. Their terms of reference and locations are given in Part I, Chapter 1, Annex 1.A.

RICs are intended to be centres of expertise on instrument types, characteristics, performance, application and calibration. They will have a technical library on instrument science and practice; laboratory space and demonstration equipment; and will maintain a set of standard instruments with calibrations traceable to international standards. They should be able to offer information, advice and assistance to Members in their Region.

Where possible, these centres will combine with a Regional Radiation Centre and should be located within or near an RTC in order to share expertise and resources.

A particular role of RICs is to assist in organizing regional training seminars or workshops on the maintenance, comparison and calibration of meteorological instruments and to provide facilities and expert advisors.

RICs should aim to sponsor the best teaching methods and provide access to training resources and media which may be beyond the resources of NMHSs. The centres will need to provide refresher training for their own experts in the latest technology available and training methods in order to maintain their capability.

Manufacturers of meteorological instrumentation systems could be encouraged to sponsor training sessions held at RICs.

5.5.2 WMO training resources

5.5.2.1 WMO education and training syllabi

WMO (2002*a*; 2002*b*) include syllabi for specialization in meteorological instruments and in meteorological telecommunications. The education and training syllabi are guidelines that need to be interpreted in the light of national needs and technical education standards.

5.5.2.2 WMO survey of training needs

WMO conducts a periodic survey of training needs by Regions, classes and meteorological specialization. This guides the distribution and kind of training events sponsored by WMO over a four-year period. It is important that Member countries include a comprehensive assessment of their need for instrument specialists in order that WMO training can reflect true needs.

5.5.2.3 WMO education and training publications

These publications include useful information for instrument specialists and their managers. WMO (1986) is a compendium in two volumes of lecture notes on training in meteorological instruments at technician level which may be used in the classroom or for individual study.

5.5.2.4 WMO training library

The library produces a catalogue (WMO, 1983) of training publications, audiovisual aids and computer diskettes, some of which may be borrowed, or otherwise purchased, through WMO.

5.5.2.5 WMO instruments and observing methods publications

These publications, including reports of CIMO working groups and rapporteurs and instrument intercomparisons, and so forth, provide instrument specialists with a valuable technical resource for training and reference.

5.5.2.6 Special WMO-sponsored training opportunities

The Managers of engineering groups should ensure that they are aware of technical training opportunities announced by WMO by maintaining contact

---

[2] Recommended by the Commission for Instruments and Methods of Observation at its ninth session (1985) through Recommendation 19 (CIMO-IX).

with their training department and with the person in their organization who receives correspondence concerning the following:

(a) Travelling experts/roving seminars/workshops: From time to time, CIMO arranges for an expert to conduct a specified training course, seminar or workshop in several Member countries, usually in the same Region. Alternatively, the expert may conduct the training event at a RIC or RTC and students in the region travel to the centre. The objective is to make the best expertise available at the lowest overall cost, bearing in mind the local situation;

(b) Fellowships: WMO provides training fellowships under its Technical Cooperation Programme. Funding comes from several sources, including the United Nations Development Programme, the Voluntary Cooperation Programme, WMO trust funds, the regular budget of WMO and other bilateral assistance programmes. Short-term (less than 12 months) or long-term (several years) fellowships are for studies or training at universities, training institutes, or especially at WMO RTCs, and can come under the categories of university degree courses, postgraduate studies, non-degree tertiary studies, specialized training courses, on-the-job training, and technical training for the operation and maintenance of equipment. Applications cannot be accepted directly from individuals. Instead, they must be endorsed by the Permanent Representative with WMO of the candidate's country. A clear definition must be given of the training required and priorities. Given that it takes an average of eight months to organize a candidate's training programme because of the complex consultations between the Secretariat and the donor and recipient countries, applications are required well in advance of the proposed training period. This is only a summary of the conditions. Full information and nomination forms are available from the WMO Secretariat. Conditions are stringent and complete documentation of applications is required.

5.5.3 Other training opportunities

5.5.3.1 Technical training in other countries

Other than WMO fellowships, agencies in some countries offer excellent training programmes which may be tailored to the needs of the candidate. Instrument specialists should enquire about these opportunities with the country or agency representative in their own country.

5.5.3.2 Training by equipment manufacturers

This type of training includes the following:

(a) New data-acquisition system purchase: All contracts for the supply of major data-acquisition systems (including donor-funded programmes) should include an adequate allowance for the training of local personnel in system operation and maintenance. The recipient Meteorological Service representatives should have a good understanding of the training offered and should be able to negotiate in view of their requirements. While training for a new system is usually given at the commissioning stage, it is useful to allow for a further session after six months of operational experience or when a significant maintenance problem emerges;

(b) Factory acceptance/installation/commissioning: Work concerned with the introduction of a major data-acquisition facility, for example, a satellite receiver or radar, provides unique opportunities for trainees to provide assistance and learn the stringent technical requirements.

    Acceptance testing is the process of putting the system through agreed tests to ensure that the specifications are met before the system is accepted by the customer and despatched from the factory.

    During installation, the supplier's engineers and the customer's engineers often work together. Other components, such as a building, the power supply, telecommunications and data processing, may need to be integrated with the system installation.

    Commissioning is the process of carrying out agreed tests on the completed installation to ensure that it meets all the specified operational requirements.

    A bilateral training opportunity arises when a country installs and commissions a major instrumentation system and trainees can be invited from another country to observe and assist in the installation.

5.5.3.3 International scientific programmes

When international programmes, such as the World Climate Programme, the Atmospheric Research and Environment Programme, the Tropical Cyclone Programme or the Tropical Ocean and Global Atmosphere Programme, conduct large-scale experiments, there may be opportunities for local instrument specialists to be associated with senior colleagues in the measurement programme and to thereby gain valuable experience.

5.5.3.4 International instrument intercomparisons sponsored by the Commission for Instruments and Methods of Observation

From time to time, CIMO nominates particular meteorological measurements for investigation as a means of advancing the state of knowledge. Instruments of diverse manufacture and supplied by Members are compared under standard conditions using the facilities of the host country. An organizing committee plans the intercomparison and, in its report, describes the characteristics and performance of the instruments.

If they can be associated with these exercises, instrument specialists would benefit from involvement in some of the following activities: experimental design, instrument exposure, operational techniques, data sampling, data acquisition, data processing, analysis and interpretation of results. If such intercomparisons can be conducted at RICs, the possibility of running a parallel special training course might be explored.

5.5.4 Budgeting for training costs

The meteorological engineering or instrumentation department of every NMHS should provide an adequate and clearly identified amount for staff training in its annual budget, related to the Service's personnel plan. A lack of training also has a cost: mistakes, accidents, wastage of time and material, staff frustration, and a high staff turnover resulting in poor quality data and meteorological products.

5.5.4.1 Cost-effectiveness

Substantial costs are involved in training activities, and resources are always likely to be limited. Therefore, it is necessary that the costs of various training options should be identified and compared, and that the cost-effectiveness of all training activities should be monitored, and appropriate decisions taken. Overall, the investment in training by the NMHS must be seen to be of value to the organization.

5.5.4.2 Direct and indirect costs

Costs may be divided into the direct costs of operating certain training courses and the indirect or overhead costs of providing the training facility. Each training activity could be assigned some proportion of the overhead costs as well as the direct operating costs. If the facilities are used by many activities throughout the year, the indirect cost apportioned to any one activity will be low and the facility is being used efficiently.

Direct operating costs may include trainee and tutor travel, accommodation, meals and daily expenses, course and tutor fees, WMO staff costs, student notes and specific course consumables, and trainee time away from work.

Indirect or overhead costs could include those relating to training centre buildings (classrooms, workshops and laboratories), equipment and running costs, teaching and administration staff salaries, WMO administration overheads, the cost of producing course materials (new course design, background notes, audiovisual materials), and general consumables used in training.

In general, overall costs for the various modes of training may be roughly ranked from the lowest to the highest as follows (depending on the efficiency of resource use):
(a) On-the-job training;
(b) Correspondence courses;
(c) Audiovisual courses;
(d) Travelling expert/roving seminar, in situ course;
(e) National course with participants travelling to a centre;
(f) Computer-aided instruction (high initial production cost);
(g) Regional course with participants from other countries;
(h) Long-term fellowships;
(i) Regional course at a specially equipped training centre.

ANNEX

REGIONAL TRAINING CENTRES

Country	*Name of centre*	*WMO Region*
Algeria	Hydrometeorological Institute for Training and Research (IHFR), Oran	I
Angola[a]	Regional Training Centre, Mulemba	I
Egypt	Regional Training Centre, Cairo	I
Kenya[b]	Institute for Meteorological Training and Research, Nairobi; and Department of Meteorology, University of Nairobi, Nairobi	I
Madagascar	École supérieure polytechnique d'Antananarivo, University of Antananarivo, Antananarivo	I
Niger	African School of Meteorology and Civil Aviation (EAMAC), Niamey; and Regional Training Centre for Agrometeorology and Operational Hydrology and their Applications (AGRHYMET), Niamey	I
Nigeria[b]	Meteorological Research and Training Institute, Lagos; and Department of Meteorology, Federal University of Technology, Akure	I
China[b]	Nanjing Institute of Meteorology, Nanjing; and China Meteorological Administration Training Centre, Beijing	II
India[b]	Telecommunication and Radiometeorological Training Centre, New Delhi; and Training Directorate, Pune	II
Iran (Islamic Republic of)	Advanced Meteorological Sciences Training Centre, Tehran	II
Iraq	Regional Training Centre, Baghdad	II
Uzbekistan	Hydrometeorological Technical School, Tashkent	II
Argentina[b]	Department of Atmospheric Science, University of Buenos Aires, Buenos Aires; and Department of Education and Training of the National Meteorological Service, Buenos Aires;	III
Brazil	Department of Meteorology, Federal University of Pará, Belém	III
Venezuela	Department of Meteorology and Hydrology, Central University of Venezuela, Caracas	III
Barbados[b]	Caribbean Institute for Meteorology and Hydrology, Bridgetown; and University of the West Indies, Bridgetown	IV
Costa Rica	Section of Atmospheric Physics, School of Physics, University of Costa Rica, San José	IV
Philippines[b]	Department of Meteorology and Oceanography, University of the Philippines; and Training Centre of the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), Quezon City	V
Israel	Postgraduate Training Centre for Applied Meteorology, Bet Dagan	VI
Italy[b]	International School of Meteorology of the Mediterranean, Erice, Sicily; and Institute of Agrometeorology and Environment Analysis for Agriculture, Florence	VI
Russian Federation[b]	Advanced Training Institute and Moscow Hydrometeorological College, Moscow; and Russian State Hydrometeorological Institute, St Petersburg	VI
Turkey	Anatolian Meteorological Technical High School, Ankara	VI

[a] RTC Angola re-opening operations are under way.

[b] These Centres have a university component.

REFERENCES AND FURTHER READING

Craig, R.L. (ed.), 1987: *Training and Development Handbook: A Guide to Human Resource Development*. McGraw-Hill, New York.

Imai, M., 1986: Kaizen: *The Key to Japan's Competitive Success*. Random House, New York.

International Organization for Standardization, 1994*a*: *Quality Management and Quality Assurance Standards – Part 1: Guidelines for Selection and Use*. ISO 9000–1; 1994, Geneva.

International Organization for Standardization, 1994*b*: *Quality Management and Quality System Elements – Part 1*: *Guidelines*. ISO 9004-1; 1994, Geneva

Moss, G., 1987: *The Trainer's Handbook*. Ministry of Agriculture and Fisheries, New Zealand.

Walton, M., 1986: *The Deming Management Method*. Putnam Publishing, New York.

World Meteorological Organization, 1983: *Catalogue of Meteorological Training Publications and Audiovisual Aids*. Third edition, Education and Training Programme Report No. 4, WMO/TD-No. 124, Geneva.

World Meteorological Organization, 1986: *Compendium of Lecture Notes on Meteorological Instruments for Training Class III and Class IV Meteorological Personnel* (D.A. Simidchiev). WMO-No. 622, Geneva.

World Meteorological Organization, 1989: *Guide on the Global Observing System*. WMO-No. 488, Geneva.

World Meteorological Organization, 1990: *Guidance for the Education and Training of Instrument Specialists* (R.A. Pannett). Education and Training Programme Report No. 8, WMO/TD-No. 413, Geneva.

World Meteorological Organization, 2002*a*: *Guidelines for the Education and Training of Personnel in Meteorology and Operational Hydrology*. Volume I: Meteorology. Fourth edition, WMO-No. 258, Geneva.

World Meteorological Organization, 2002*b*: *Initial Formation and Specialisation of Meteorological Personnel: Detailed Syllabus Examples*. WMO/TD-No. 1101, Geneva.

APPENDIX

LIST OF CONTRIBUTORS TO THE GUIDE

Artz, R. (United States)

Ball, G. (Australia)

Behrens, K. (Germany)

Bonnin, G.M. (United States)

Bower, C.A. (United States)

Canterford, R. (Australia)

Childs, B. (United States)

Claude, H. (Germany)

Crum, T. (United States)

Dombrowsky, R. (United States)

Edwards, M. (South Africa)

Evans, R.D. (United States)

Feister, E. (Germany)

Forgan, B.W. (Australia)

Hilger, D. (United States)

Holleman, I. (Netherlands)

Hoogendijk, K. (Netherlands)

Johnson, M. (United States)

Klapheck, K.-H. (Germany)

Klausen, J. (Switzerland)

Koehler, U. (Germany)

Ledent, T. (Belgium)

Luke, R. (United States)

Nash, J. (United Kingdom)

Oke, T. (Canada)

Painting, D.J. (United Kingdom)

Pannett, R.A. (New Zealand)

Qiu Qixian (China)

Rudel, E. (Austria)

Saffle, R. (United States)

Schmidlin, F.J. (United States)

Sevruk, B. (Switzerland)

Srivastava, S.K. (India)

Steinbrecht, W. (Germany)

Stickland, J. (Australia)

Stringer, R. (Australia)

Sturgeon, M.C. (United States)

Thomas, R.D. (United States)

Van der Meulen, J.P. (Netherlands)

Vanicek, K. (Czech Republic)

Wieringa, J. (Netherlands)

Winkler, P. (Germany)

Zahumensky, I. (Slovakia)

Zhou Weixin (China)