CHAPTER 3. MEASUREMENT OF ATMOSPHERIC PRESSURE

3.1 GENERAL

3.1.1 Definition

The atmospheric pressure on a given surface is the force per unit area exerted by virtue of the weight of the atmosphere above. The pressure is thus equal to the weight of a vertical column of air above a horizontal projection of the surface, extending to the outer limit of the atmosphere.

Apart from the actual pressure, pressure trend or tendency has to be determined as well. Pressure tendency is the character and amount of atmospheric pressure change for a three-hour or other specified period ending at the time of observation. Pressure tendency is composed of two parts, namely the pressure change and the pressure characteristic. The pressure change is the net difference between pressure readings at the beginning and end of a specified interval of time. The pressure characteristic is an indication of how the pressure has changed during that period of time, for example, decreasing then increasing, or increasing and then increasing more rapidly.

3.1.2 Units and scales

The basic unit for atmospheric pressure measurements is the pascal (Pa) (or newton per square metre, Nm^{-2}). It is accepted practice to add the prefix “hecto” to this unit when reporting pressure for meteorological purposes, making the hectopascal (hPa), equal to 100 Pa, the preferred terminology. This is largely because one hectopascal equals one millibar (mbar), the formerly used unit. Further details on the mandatory use of SI units are explained in the present volume, Chapter 1. Note that units used for barometer readings such as "mm Hg", "in Hg" or "mbar" are not defined within SI and may not be used for the international exchange of data when reporting atmospheric pressure (see also Annex 3.A of this chapter).

In this chapter only the unit hPa is used.

3.1.3 Meteorological requirements

Analysed pressure fields are a fundamental requirement of the science of meteorology. It is imperative that these pressure fields be accurately defined as they form the basis for all subsequent predictions of the state of the atmosphere. Pressure measurements must be as accurate as technology allows, within realistic financial constraints, and there must be uniformity in the measurement and calibration procedures across national boundaries.

The level of accuracy needed for pressure measurements to satisfy the requirements of various meteorological applications has been identified by the respective WMO commissions and is outlined in the present volume, Chapter 1, Annex 1.A, which is the primary reference for measurement specifications in the present Guide.

These requirements should be considered achievable for new barometers in a strictly controlled environment, such as those available in a properly equipped laboratory. They provide an appropriate target uncertainty for barometers to meet before their installation in an operational environment.

For barometers installed in an operational environment, practical constraints will require well-designed equipment for an NMHS to maintain this target uncertainty. Not only the barometer itself, but the exposure also requires special attention. Nevertheless, the performance of the operational network station barometer should not be below the stated criteria.

3.1.4 **Methods of measurement and observation**

3.1.4.1 ***General measurement principles***

For meteorological purposes, atmospheric pressure is generally measured with electronic barometers, aneroid barometers or hypsometers. The latter class of instruments, which depend on the relationship between the boiling point (temperature) of a liquid and the atmospheric pressure, has so far seen only limited application and will not be discussed in depth in this publication.

Mercury barometers are still in use, but no longer recommended, taking into account the Minamata Convention on Mercury (see the present volume, Chapter 1, 1.4.2). NMHSs are encouraged to urgently take appropriate measures to replace mercury barometers with modern alternatives (see 3.1.4.5). Information on observation practices with mercury barometers is maintained in Annex 3.A only to inform the reader on this obsolete practice.

Most barometers with recent designs make use of transducers which transform the sensor response into pressure-related quantities. These are subsequently processed by using appropriate electrical integration circuits or data-acquisition systems with appropriate smoothing algorithms. A time constant of about 10 s (and definitely no greater than 20 s) is desirable for most synoptic barometer applications.

There are several general methods for measuring atmospheric pressure and these are outlined in the following paragraphs.

A membrane of elastic substance, held at the edges, is deformed if the pressure on one side is greater than on the other. In practice, this is achieved by using a completely or partially evacuated closed metal capsule containing a strong metal spring to prevent the capsule from collapsing due to external atmospheric pressure. Mechanical or electrical means are used to measure the deformation caused by the pressure differential between the inside and outside of the capsule. This is the principle of the well-known aneroid barometer.

Pressure sensor elements comprising thin-walled nickel alloy cylinders, surrounded by a vacuum, have been developed. The natural resonant frequency of these cylinders varies as a function of the difference in pressure between the inside of the cylinder, which is at ambient atmospheric pressure, and the outside of the cylinder, which is maintained as a vacuum. In fact, these instruments measure the pressure by sensing the density of the gas (air) inside.

Absolute pressure transducers, which use a crystalline quartz element, are also commonly used. Pressure exerted via flexible bellows on the crystal face causes a compressive force on the crystal. On account of the crystal’s piezoresistive properties, the application of pressure alters the balance of an active Wheatstone bridge. Balancing the bridge enables accurate determination of the pressure. These types of pressure transducers are virtually free of hysteresis effects.

3.1.4.2 ***General exposure requirements***

It is important that the location of barometers at observation stations be selected with great care. The main requirements of the place of exposure are good light to read out (in case of manual readings), a draught-free environment, a solid, non-vibrating mounting, and protection against rough handling.

Special effort in positioning is required to prevent any artificial wind impact. Such impact is typical for indoor measurement due to the build-up of pressure outside the building and generating errors which are sometime larger than 1 hPa. For further details, see 3.1.4.3.2.

3.1.4.3 *Sources of error: general comments*

Errors in the measurement of pressure may be caused by an inappropriate placement of the instrument. The instrument must be placed in an environment where external effects will not lead to measurement errors. These effects include wind, radiation and temperature, shocks and vibrations, fluctuations in the electrical power supply, and pressure shocks. It is important that every meteorological observer or technical staff should fully understand these effects and be able to assess whether any of them are affecting the accuracy of the readings of the barometer in use.

In case of manual readings, the instrument (or its display) should be easy to read. Instruments must be designed so that the resolution of their readings is better than the required measurement uncertainty, that is, rounding error does not increase significantly the uncertainty of the measurement results.

3.1.4.3.1 The effects of temperature

Instrument readings should not be affected by temperature variations. Instruments are suitable only if at least one of the following conditions is met:

(a) The instrument is designed to be temperature independent or compensated for the whole temperature range, to be proven by adequate calibration and tests;

(b) Procedures for correcting the readings for temperature effects are developed and implemented to ensure the required uncertainty;

(c) The pressure sensing element is placed in an environment where the temperature is stabilized so that the required uncertainty is met.

Most instruments measure the temperature of the pressure sensor to compensate for temperature effects. It is necessary to control and calibrate these temperature-compensating functions as part of the standard calibration activity.

3.1.4.3.2 The effects of wind

It should be noted that the effects of wind apply to all types of barometers. More information on wind effects is found in Liu and Darkow (1989).

A barometer will not give a true reading of the static pressure if it is influenced by gusty wind. Its reading will fluctuate with the wind speed and direction and with the magnitude and sign of the fluctuations, depending also on the nature of the room’s openings and their position in relation to the direction of the wind. At sea, error is always present due to the ship’s motion. A similar problem will arise if the barometer is installed in an air-conditioned room.

Wind can often cause dynamic changes of pressure in the room where the barometer is placed. These fluctuations are superimposed on the static pressure and, with strong and gusty wind, may amount to up to 2 or 3 hPa. It is usually impractical to correct for such fluctuations because the “pumping” effect is dependent on both the direction and the force of the wind, as well as on the local circumstances of the barometer’s location. Thus, the “mean value” does not represent the true static pressure. When comparing barometers in different buildings, the possibility of a difference in readings due to the wind effect should be borne in mind.

It is possible to overcome this effect to a very large extent by using a static head between the exterior atmosphere and the inlet port of the barometer. Details concerning the operating principles of static heads can be found in several publications (Miksad, 1976; United States Weather Bureau, 1963). Aneroid and electronic barometers usually have simple connections to allow for the use of a static head, which should be located in an open environment not affected by the proximity of buildings. The design of such a head requires careful attention. Static pressure heads are commercially available, but there is limited published literature on intercomparisons to demonstrate their performance (WMO, 2012).

3.1.4.3.3 The effects of air conditioning

Air conditioning may create a significant pressure differential between the inside and outside of a room. Therefore, if a barometer is to be installed in an air-conditioned room, it is advisable to use a static head with the barometer which will couple it to the air outside the building.

3.1.4.3.4 The effects of hysteresis

Some barometers (in particular aneroid barometers) are affected by hysteresis, with an impact larger than 0.1 hPa. To demonstrate that any hysteresis is within the required measurement uncertainty, calibrations must be performed in both ascending and descending pressure steps.

3.1.4.3.5 Transport and use in a non-stabilized environment

Barometers may be sensitive to vibrations and shocks affecting the adjustment of the equipment. Special care must be taken to avoid any shock impact during transport and the instruments should be placed in a vibration-free environment.

3.1.4.4 *Maintenance: general comments*

The following maintenance procedures should be considered:

(a) The instruments and especially the pressure inlet should be kept clean and free from obstruction;

(b) The installation height of the sensing instrument and the mounting should be checked regularly;

(c) The instruments must be calibrated (and adjusted if appropriate) regularly; the interval between two calibrations must be short enough to ensure that the total absolute measurement error will meet the uncertainty requirements;

(d) Any variations in the uncertainty (long term and short term) must be much smaller than those outlined in the present volume, Chapter 1, Annex 1.A. If some instruments have a history of drift in calibration, they will be suitable operationally only if the period between calibrations is short enough to ensure the required measurement uncertainty at all times;

(e) If the instrument has to be calibrated away from its operational location, the method of transportation employed must not affect the stability or accuracy of the instrument; effects that may alter the calibration of the instrument include mechanical shocks and vibrations, displacement from the vertical position, and large pressure variations that may be encountered during transportation by air.

3.1.4.5 *Implications of the Minamata Convention for pressure measurement*

The UNEP Minamata Convention on Mercury came into force globally in August 2017 and bans all production, import and export of mercury barometers (see the present volume, Chapter 1, 1.4.2). Therefore, mercury barometers are no longer recommended and it is strongly encouraged to take appropriate measures to replace such barometers with modern alternatives. Electronic barometers provide an economical, accurate and reliable alternative to these dangerous, mercury-based instruments and offer significant advantages in terms of data storage and real-time data display.

3.2 ELECTRONIC BAROMETERS

Most barometers with recent designs make use of transducers that transform the sensor response into a pressure-related electrical quantity in the form of either analogue signals (for example, voltage (DC or AC with a frequency related to the actual pressure)), or digital signals (for example, pulse frequency or with standard data communication protocols such as RS232, RS422, RS485 or IEEE488). Analogue signals can be displayed on a variety of electronic meters. Monitors and data-acquisition systems, such as those used in AWSs, are frequently used to display digital outputs or digitized analogue outputs.

Current digital barometer technology employs various levels of redundancy to improve the long-term stability and accuracy of the measurements. One technique is to use three independently operating sensors under centralized microprocessor control. Even higher stability and reliability can be achieved by using three completely independent barometers, incorporating three sets of pressure transducers and microprocessors. Each configuration has automatic temperature compensation from internally mounted temperature sensors. Triple redundancy ensures excellent long-term stability and measurement accuracy, even in the most demanding applications. These approaches allow for continuous monitoring and verification of the individual sensor performances.

3.2.1 Integrated-circuit-based variable capacitive sensors

Capacitive pressure sensors use the electrical property of capacitance to measure the displacement of a diaphragm. The diaphragm is an elastic pressure sensor displaced in proportion to changes in pressure. It acts as one plate of a capacitor that detects strain due to applied pressure to become a variable capacitor. The change in value of the capacitance causes this electrical signal to vary. This is then conditioned and displayed on a device calibrated in terms of pressure. Common technologies use metal, ceramic and silicon diaphragms. Because this measurement is temperature dependent, sensor temperature is also measured for compensation to meet the accuracy requirements.

Silicon-diaphragm sensors are popular in integrated circuit technology today (with a size of about 1 µm). For this technique the absolute pressure is measured using a vacuum-based chamber (pressure smaller than 10^{-3} hPa).

3.2.2 Digital piezoresistive barometers

Measurements of atmospheric pressure have become possible by utilizing the piezoelectric (piezoresistive) effect. A common configuration features four measuring resistors placed onto the flexible surface of a monolithic silicon substratum interconnected to form a Wheatstone bridge circuit.

Axially loaded crystalline quartz elements are used in digital piezoresistive barometers and are a type of absolute pressure transducer. Crystalline quartz has been chosen because of its piezoelectric properties, stable frequency characteristics, small temperature effects and precisely reproducible frequency characteristics. Pressure applied to an inlet port causes an upward axial force by means of flexible bellows, thus resulting in a compressive force on the quartz crystal element. Since the crystal element is a substantially rigid membrane, the entire mechanical structure is constrained to minute deflections, thereby virtually eliminating mechanical hysteresis.

The fully active Wheatstone bridge mentioned above may consist either of semiconductor strain gauges or piezoresistive gauges. The strain gauges are either bonded to a thin circular diaphragm, which is clamped along its circumference, or atomically diffused into a silicon diaphragm configuration. In the case of diffused devices, the silicon integrated chip itself is the diaphragm. Applied pressure presents a distributed load to the diaphragm which, in turn, provides bending stress and resultant strains to which the strain gauges react. This stress creates a strain that is proportional to the applied pressure and which results in a bridge imbalance. The bridge output is then proportional to the net difference in pressure acting upon the diaphragm.

This mode of operation is based on the fact that the atmospheric pressure acts on the sensor element covering a small evacuated cell, through which the resistors are submitted to compressive and tensile stresses. By the piezoelectric effect, the values of resistance change proportionally with atmospheric pressure. To eliminate temperature errors, the instrument often incorporates a built-in thermostat.

The output from the Wheatstone bridge, which is fed from a direct-current source, is transduced into a standard signal by an appropriate amplifier. A light-emitting diode (LED) or liquid crystal display usually presents the measured pressure values.

In a modern version of the pressure transducer using a piezoelectric transducer, two resonance frequencies of the piezoelectric element are determined. By calculating a linear function of these frequencies and with an appropriate set of variables obtained after calibration, a pressure is calculated by a microprocessor which is independent of the temperature of the sensor.

3.2.3 **Cylindrical resonator barometers**

Cylindrical resonator barometers use a sensing element which is a thin-walled cylinder of nickel alloy. This is electromagnetically maintained in a "hoop" mode of vibration. The input pressure is sensed by the variation it produces in the natural resonant frequency of the vibrating mechanical system. Cylinder wall movement is sensed by a pick-up coil whose signal is amplified and fed back to a drive coil. The air pressure to be measured is admitted to the inside of the cylinder, with a vacuum reference maintained on the outside. The natural resonant frequency of vibration then varies precisely with the stress set up in the wall due to the pressure difference across it. An increase in pressure gives rise to an increase in frequency.

The thin cylinder has sufficient rigidity and mass to cater for the pressure ranges over which it is designed to operate, and is mounted on a solid base. The cylinder is placed in a vacuum chamber and its inlet is connected to the free atmosphere for meteorological applications. Since there is a unique relationship between the natural resonant frequency of the cylinder and the pressure, the atmospheric pressure can be calculated from the measured resonant frequency. However, this relationship, determined during calibration, depends on the temperature and the density of the gas. Temperature compensation is therefore required and the air should be dried before it enters the inlet.

3.2.4 **Aneroid displacement transducers**

Contact-free measurement of the displacement of the aneroid capsule is a virtual necessity for precision pressure-measuring instruments for meteorological applications. A wide variety of such transducers are in use, including capacitive displacement detectors, potentiometric displacement detectors, strain gauges placed at strategic points on the sensor, and force-balanced servo-systems which keep the sensor dimensions constant regardless of pressure.

All sensitive components must be encased in a die-cast housing. Unless designed with an adequate temperature compensation, this housing must be kept at a constant temperature by an electronically controlled heater. Condensation of water vapour must be completely prevented. An effective technique is to put a hygroscopic agent, such as silica gel crystals, into the die-cast housing and to prevent water vapour diffusion into the housing by connecting a long plastic tube (approximately 25 m) with a bore of 2 mm or less, between the pressure port and a static head (see 3.1.4.3.2).

The pressure-sensor housing must be airtight, allowing external connection to the compartment where the pressure is to be measured.

3.2.5 Exposure of electronic barometers

Details on general exposure requirements are provide in 3.1.4.2. Electronic barometers should be mounted away from electromagnetic sources; where this is not possible, the wires and casing should be shielded.

3.2.6 Reading electronic barometers

An electronic barometer measures the atmospheric pressure of the surrounding space or any space that is connected to it via a tube. In general, the barometer should be set to read the pressure at the level of the instrument. On board a ship or at low-level land stations, however, the instrument may be set to indicate the pressure at MSL, provided that the difference between the station pressure and the sea-level pressure can be regarded as constant.

Electronic barometers give accurate readings on a digital read-out, normally scaled in hPa, but readily adaptable to other units if required. Provision can usually be made for digital recording. Trend in pressure changes can be presented if the unit is microprocessor-controlled.

Circuits may be attached to primary transducers which correct the primary output for sensor non-linearities and temperature effects and which convert output to standard units. Standard modern barometer versions comprise the barometer sensor, the microcomputer unit (including the display) and an interface circuit to communicate with any data logger or AWS.

Electronic barometers which have more than one transducer or sensing element generally calculate a weighted mean of the outputs from each of the sensors and establish the resultant pressure with a resolution of at least 0.1 hPa. During calibration, each of the sensing elements can be checked with a resolution of at least 0.01 hPa.

3.2.7 Sources of error

The accuracy of electronic barometers depends on the uncertainty of the barometer’s calibration, the effectiveness of the barometer’s temperature compensation (residual air method, temperature measurement and correction, use of a thermostat) and the drift with time.

3.2.7.1 *Drift between calibrations*

Drift between calibrations is one of the key sources of error with barometers. It is often greater when the barometer is new and decreases with the passage of time. Step jumps in calibration may occur.

In order to maintain the acceptable performance of a barometer, the calibration corrections applied to the readings must be checked at relatively frequent intervals, for example, starting annually, for early detection and replacement of defective instruments.

The need to check frequently the calibration of electronic barometers imposes an additional burden on NMHSs, particularly on those with extensive barometer networks. The ongoing cost of calibration must be taken into consideration when planning to replace mercury barometers with electronic barometers.

3.2.7.2 ***Temperature***

Most electronic barometers are adequately compensated for temperature, which can be proven during calibration or testing. In the case that an electronic barometer is not sufficiently compensated for temperature, it must be kept at a constant temperature if the calibration is to be maintained. The temperature should be near the calibration temperature. Electronic barometers that are not temperature-controlled are usually prone to greater error. Most depend on accurate temperature measurement of the sensing element and electronic correction of the pressure. This assumes that there are no thermal gradients within the sensing element of the barometer. In situations where the temperature changes reasonably quickly, this can result in short-term hysteresis errors in the measured pressure.

The change in calibration may also be dependent on the thermal history of the barometer. Prolonged exposure to temperature changes may result in medium- to long-term calibration shifts.

The electronics of the barometer can also introduce errors if it is not held at the same temperature as the sensing element. Electronic barometers are very often used in extreme climatic conditions, especially in AWSs. In these situations, the barometer can be exposed to temperatures well in excess of its manufacturer's design and calibration specifications.

3.2.7.3 ***Electrical interference***

As with all sensitive electronic measurement devices, electronic barometers should be shielded and kept away from sources of strong magnetic fields, such as transformers, computers, radar, and so forth. Although this is not often a problem, it can cause an increase in noise, with a resultant decrease in the precision of the device.

3.2.7.4 ***Nature of operation***

Apparent changes in the calibration of an electronic barometer can be caused by differences in the way in which the barometer is operated during calibration, as compared with its operational use. A pressure read on a barometer that is run continuously and, therefore, warmed up will read differently from that read in a pulsed fashion every few seconds.

3.3 ANEROID BAROMETERS

3.3.1 Construction requirements

The principal components are a closed metal chamber, completely or partly evacuated, and a strong spring system that prevents the chamber from collapsing under the external atmospheric pressure. At any given pressure, there will be an equilibrium between the force caused by the spring and that of the external pressure.

The aneroid chamber may be made of materials (steel or beryllium copper) that have elastic properties such that the chamber itself can act as a spring.

A means is required to detect and display the changes in deflection which occur. This may be a system of levers that amplify the deflections and drive a pointer over a scale graduated to indicate the pressure. Alternatively, a ray of light may be deviated over the scale. Instead of these mechanical analogue techniques, certain barometers are provided with a manually operated micrometer whose counter indicates the pressure directly in tenths of a hectopascal. A reading is taken when a luminous indicator signals that the micrometer has just made contact with the aneroid. This type of aneroid is portable and robust.

3.3.2 Achievable measurement uncertainty

The achievable measurement uncertainty of 0.3 hPa is possible for a well-designed and constructed aneroid barometer. To achieve this uncertainty, apart from a regular, frequent calibration to reduce calibration drift (as already mentioned for electronic barometers in 3.2.7.1) the following rules should be considered:

(a) It should be compensated for temperature so that the reading does not change by more than 0.3 hPa for a change in temperature of 30 K;

(b) The scale errors at any point should not exceed 0.3 hPa and should remain within this tolerance over periods of at least one year, when in normal use;

(c) The hysteresis should be sufficiently small to ensure that the difference in reading before a change in pressure of 50 hPa and after a return to the original value does not exceed 0.3 hPa;

(d) It should be capable of withstanding ordinary transit risks without introducing inaccuracies beyond the limits specified above.

3.3.3 Exposure of aneroid barometers

Details on general exposure requirements are provide in 3.1.4.2. The place selected for mounting the device should preferably have a fairly uniform temperature throughout the day. Therefore, a location is required where the barometer is shielded from the direct rays of the sun and from other sources of either heat or cold, which can cause abrupt and marked changes in its temperature.

3.3.4 Reading aneroid barometers

3.3.4.1 *Accuracy of readings*

An aneroid barometer should always be read in the same orientation (vertical or horizontal) as during calibration. It should be tapped lightly before being read. As far as possible, it should be read to the nearest 0.1 hPa. Optical and digital devices are available to reduce the errors caused by mechanical levers. The readings should be corrected for instrumental errors, but the instrument is usually assumed to be sufficiently compensated for temperature, and it needs no correction for gravity.

3.3.4.2 *Reductions applied to barometers*

In general, aneroid barometers should be set to read the pressure at the level of the instrument. On board a ship or at low-lying land stations, however, the instrument may be set to indicate the pressure at MSL, provided that the difference between the station pressure and the sea-level pressure can be regarded as constant.

3.3.5 Sources of error

3.3.5.1 *Incomplete compensation for temperature*

In an aneroid barometer, if the spring is weakened by an increase in temperature, the pressure indicated by the instrument will be too high. This effect is generally compensated for in one of the following ways:

(a) By means of a bimetallic link in the lever system;

(b) By leaving a certain amount of gas inside the aneroid chamber.

In most ordinary aneroid barometers, the compensation obtained by these methods is complete only at one particular compensation pressure. It is desirable that all aneroid barometers and barographs used at meteorological stations should be properly compensated for temperatures over the full range of pressure. In digital read-out systems suitable for automation, such complete corrections can be applied as part of the electronic system.

3.3.5.2 *Elasticity errors*

An aneroid barometer may be subjected to a large and rapid change in pressure. For example, a strong gust of wind would cause an aneroid barometer to experience a rapid increase in pressure followed by a more gradual return to the original value. In such circumstances, the instrument will, owing to hysteresis, indicate a slightly different reading from the true pressure; a considerable time may elapse before this difference becomes negligible. However, since aneroids and barographs at surface stations are not usually directly exposed to such pressure changes, their hysteresis errors are not excessive.

There is also a secular error caused by slow changes in the metal of the aneroid capsule. This effect can be allowed for only by comparison at regular intervals, for example, annually, with a standard barometer. A good aneroid barometer should retain an accuracy of 0.1 hPa over a period of one year or more. In order to detect departures from this accuracy by individual barometers, a regular inspection procedure with calibration and adjustment as necessary should be instituted.

3.4 BAROGRAPHS

3.4.1 General requirements

Of the various types of barographs, only aneroid barographs are dealt with in detail here. For synoptic purposes, it is recommended that charts for barographs:

(a) Be graduated in hPa;

(b) Be readable to 0.1 hPa;

(c) Have a scale factor of 10 hPa to 1.5 cm on the chart.

In addition, the following requirements are desirable:

(a) The barograph should employ a high quality aneroid unit (see 3.4.2);

(b) The barograph should be compensated for temperature, so that the reading does not change by more than 1 hPa for a 20 K change in temperature;

(c) Scale errors should not exceed 1.5 hPa at any point;

(d) Hysteresis should be sufficiently small to ensure that the difference in reading before a change in pressure of 50 hPa and after a return to the original value does not exceed 1 hPa;

(e) There should be a time-marking arrangement that allows the marks to be made without lifting the cover;

(f) The pen arm should be pivoted in a "gate", the axis of which should be inclined in such a way that the pen rests on the chart through the effects of gravity. A means of adjustment should be provided for setting the position of the pen.

Marine barographs are subject to special requirements, which are considered in Volume III, Chapter 4 of the present Guide.

3.4.2 Construction of barographs

The principle of the aneroid barograph is similar to that of the aneroid barometer, except that a recording pen is used instead of a pointer. This involves some change in the design of the capsule stack, and usually means a decrease in the overall magnification and an increase in the number and size of the capsules used.

The "control" of the barograph may be expressed as the force required to move the pointer over one unit of the scale (1 hPa) and is, thus, equal to the force required to prevent the pen from moving when the pressure changes by 1 hPa. It is a measure of the effect that friction is likely to have on the details of the record.

The force required to overcome the movement of the capsule when the pressure changes by 1 hPa is 100 A newtons, where A is the effective cross-sectional area of the capsule in square metres. If the magnification is X, the force necessary to keep the pen from moving is 100 A/X newtons and varies as A/X. For a given type of capsule and scale value, the value of X will be largely independent of A, so that the control of a barograph pen may be considered to vary approximately with the effective cross-sectional area of the capsule.

3.4.3 Exposure of barographs

Details on general exposure requirements are provide in 3.1.4.2. The barograph should be placed at a location where it is unlikely to be tampered with by unauthorized persons. Mounting the barograph on a sponge rubber cushion is a convenient means of reducing the effects of vibration. The site selected should be clean and dry. The air should also be relatively free of substances which would cause corrosion and fouling of the mechanism.

It is important to place the instrument so that its face will be at a convenient height to be read at eye-level under normal operating conditions with a view to minimizing the effects of parallax. The exposure ought to be such that the barometer is uniformly illuminated, with artificial lighting being provided if necessary.

3.4.4 Sources of error

In addition to the sources of error mentioned for the aneroid (see 3.3.5), the friction between the pen and the paper is important. The control of the pen depends largely on the effective cross-section of the aneroid. In a well-made barograph, the friction of the pen is appreciably greater than the total friction at all the pivots and bearings of the instrument; special attention should, therefore, be given to reduce such errors, for example, by having a sufficiently large aneroid capsule.

A high quality barograph should be capable of an uncertainty of about 0.2 hPa after corrections have been applied and should not alter for a period of one or two months. The barometric change read from such a barograph should usually be obtained within the same limits.

3.4.5 Reading a barograph

The barograph should be read without touching the instrument. The time mark and any inspection of the instrument involving lifting the cover, and so on, should always be made after the reading is completed.

3.4.5.1 *Accuracy of readings*

The chart should be read to the nearest 0.1 hPa. The barometric change should be obtained within the same resolution limits.

3.4.5.2 *Corrections to be applied to barograph readings*

The temperature compensation of each individual instrument should be tested before the instrument is used, and the scale factor should be adjusted by testing in a vacuum chamber. If the barograph is used only to find the barometric change, the corrections are not usually applied to the readings. In this case, the accurate setting of the pen position is not important. When absolute pressure values are required from the barograph, the record should be compared with the reading of an electronic barometer or a good aneroid barometer at least once every 24 h and the desired values found by interpolation.

3.4.5 Transport

If a barograph has to be transported by air or transported at a high altitude, the pen arm should be disconnected and precautions should be taken to ensure that the mechanism is able to withstand the overload caused by exceeding the normal measuring range of the instrument.

3.5 BAROMETRIC CHANGE AND PRESSURE TENDENCY

3.5.1 Pressure tendency and pressure tendency characteristics

At surface synoptic observing stations, pressure tendency and the pressure tendency characteristic should be derived from pressure observations from the last 3 h (over 24 h in tropical regions). Typically, the pressure tendency characteristic can be expressed by the shape of the curve recorded during the 3 h period preceding an observation. In the case of hourly observations, the amount and characteristic can be based on only four observations, and misinterpretations may result. Therefore, it is recommended that the characteristic should be determined on a higher frequency of observations, for example with 10-min intervals (WMO, 1985). Nine types of pressure tendency characteristics are defined (see WMO, 2011).

3.5.2 Measurement of a barometric change

Several methods are available to stations making observations at least every 3 h, as follows:

(a) Digital electronic barometers usually display the pressure tendency together with the actual pressure;

(b) The change can be read directly from a barograph;

(c) The change can be obtained from appropriate readings of the barometer, corrected to station level.

The error of a single barometric reading is mainly random, assuming that the barometer functions perfectly. Therefore, when two independent readings are subtracted to find the amount of change, the errors may be cumulative. Errors are partly systematic in nature, so that during the relatively short period of 3 h, the errors are likely to have the same sign and would therefore be diminished by subtraction.

3.6 TRACEABILITY ASSURANCE AND CALIBRATION

3.6.1 General comments

In view of the importance of accurate pressure observations, especially for aeronautical and synoptic purposes, and of the various possible errors to which barometers are subject, traceability assurance and regular calibration of barometers has a very high importance. Starting in the 1960s, a concept of barometer comparison, including designated regional standard barometers in each WMO regional association, had been used to ensure traceability of pressure measurements. This concept was discontinued by Decision 36 (EC-69) made by the WMO Executive Council at its sixty-ninth session in 2017. Currently, the traceability of atmospheric pressure measurements to SI units can be provided more efficiently and economically through an unbroken traceability chain and a new "strategy for traceability assurance" is implemented instead (see the present volume, Chapter I, Annex 1.B).

Some guidance is given in the following sections regarding the equipment to be used for laboratory or mobile calibration and for field checks. Definitions and general comments on calibration can be found in Volume V, Chapter 4 of the present Guide; while guidance on the computation of calibration uncertainties can be found in WMO (2015).

3.6.2 **Laboratory calibration**

Laboratory calibration of barometers should be carried out regularly by calibration laboratories with ISO/IEC 17025 accreditation or by an NMI service covered by a CIPM MRA. If a suitable laboratory is not available, traceability to SI should be assured according to the strategy for traceability assurance as described in the present volume, Chapter 1, Annex 1.B.

In general, calibrations can be performed at different locations. To achieve lower uncertainties the calibration should be performed at a permanent calibration laboratory situated at a fixed location. Under such circumstances more sensitive primary standards can be used, the environmental conditions (for example, temperature and humidity) can be controlled very well and a vibration-proof set-up can be realized.

If the instruments to be calibrated cannot be moved to a permanent calibration laboratory regularly, the calibrations can be performed with mobile calibration equipment on-site in a building at the observation site or in a specially equipped vehicle. As the environmental conditions cannot be controlled so precisely as in a permanent calibration laboratory, the achievable uncertainties are usually larger.

3.6.2.1 ***General equipment set-up***

In most cases calibration equipment includes a pressure controller in combination with the reference barometer that is traceable to SI. Pressure controllers regulate the pressure in a hose with the connected instrument to be calibrated. A vacuum pump and pressure supply are connected to the pressure controller. It is highly recommended to use a pressurized gas cylinder with dry, clean air with very high purity as the pressure source. The container must be equipped with a pressure-reducing valve. A micro-filter has to be attached between the pressure-reducing valve and the hose to the pressure controller. Data from the reference barometer are used as the reference data, not the data from the controller. Purified nitrogen may also be used for some barometers. However, for barometers using a technology based on the measurement on air density (such as cylindrical resonator barometers) nitrogen may not be used because the density of air differs from the density of nitrogen.

The following aspects based on European Association of National Metrology Institutes (EURAMET) guidelines (EURAMET, 2017) should also be taken into account:

(a) The whole equipment must be protected from direct sunlight and any source of heat.

(b) The instruments to be calibrated should be placed as close as possible to the reference instrument and at the same height.

(c) The pressure reference levels of both instruments should be as close as possible. If there are differences they have to be taken in account for corrections and uncertainties.

(d) The equipment needs time for warming and acclimatization to reach thermal equilibrium in the whole system.

(e) All barometers measure pressure using techniques that are sensitive to temperature. Therefore, these instruments are temperature compensated (mechanically or by appropriate software). When barometers are used within a wider temperature range than at normal indoor temperatures, the barometers must be calibrated or tested at a number of temperatures to be representative for that specific range.

(f) The calibration should be performed at an ambient temperature stable to within ±1 °C. This temperature should be representative for the range used in operational conditions, typically lying between 18 °C and 28 °C. Temperature should be recorded.

(g) Normally the calibration of meteorological pressure instruments is performed in absolute pressure mode so the air density has no effect. If the air density has an effect on the calibration result, not only the ambient temperature, but also the atmospheric pressure and the relative humidity are to be recorded.

(h) The workplace should be kept clean and well organized.

3.6.2.2 ***Laboratory standards***

The reference instrument must be traceable to national or international standards and the uncertainty should be better than that of the instrument to be calibrated. The ratio of the uncertainty of the instrument to be calibrated to that of the reference should be, if practicable, at least two.

3.6.2.2.1 Pressure controller with internal reference

Pressure controllers can be used as working standards, but only if the measurement uncertainty is within the required limits and traceable to SI (WMO, 2010).These controllers work in absolute pressure mode. The preselected pressure is generated by gas supply, vacuum pump and valves. The internal pressure gauge is used as reference and for regulation of the pressure. The devices under test are connected directly or via pressure hose. A slight drift may occur so the pressure controller must be recalibrated in regular intervals. Either the whole pressure controller should be sent to the calibration laboratory or only the internal pressure reference, which can be uninstalled. An uncertainty better than 0.1 hPa is possible.

3.6.2.2.2 Pressure controller with an external reference

In this case the internal pressure controller has a reduced precision or cannot be calibrated to be traceable to SI. An external precision pressure gauge is used as working standard. It is connected in parallel to the device under test. Maintenance and calibration of the external reference is easier than with an internal reference. An uncertainty better than 0.05 hPa can be achieved.

Examples of such external references, with high stability (less than 0.1 hPa in 10 years), excellent temperature compensation (better than 0.001 hPa K^{-1}) and without hysteresis are typically high precision electrical digital barometers that use the technology explained in 3.2. These types of reference barometers are highly efficient because they can be used in an automatic calibration environment requiring limited human resources. Despite high stability, it is recommended to calibrate this reference with SI-traceable equipment every year.

3.6.2.2.3 Piston gauges

A piston gauge is a primary standard and offers the lowest possible uncertainties and the highest stability. Due to its ultra-low drift, a recalibration interval of five years is recommended. The uncertainty is about 0.05 hPa or less. Although they are primary standards, they are often used also as working standards.

There are two principles based on a piston–cylinder system made of tungsten carbide. The effective area of the piston has been determined by an accredited calibration laboratory or an NMI. The temperature is measured with a PRT and the change of the effective area due to the change of temperature is calculated permanently by the piston gauge controller.

The piston rotates in a cylinder driven by a motor. The surface of the piston and the cylinder is ultra-smooth, cleaned and there is no lubrication except the molecules of the used gas.

An additional pressure controller is needed in any case, so the investment is by far the highest.

In absolute pressure mode built-in vacuum gauges are needed for both systems. Due to the relatively complicated calibration of these vacuum gauges, external vacuum gauges are recommended. In most cases vacuum-gauges suffer from the problem of drift so the calibration intervals are shorter than the calibration interval of the piston gauge itself. The uncertainty of the vacuum-gauge must be taken into account.

Piston gauges with a dynamometer gauge

The preselected pressure is generated by the pressure controller. The piston gauge and the devices under test are connected in parallel via a pressure hose. The generated pressure acts on the piston that is connected to a dynamometer which measures the force. The area around the dynamometer is evacuated so there is only a very low force due to the residual gas.

With known temperature-corrected effective area and the measured force, the pressure is calculated. The vacuum is measured with a vacuum gauge. The residual pressure must be taken into account by the piston gauge controller.

Regular adjustments of the dynamometer zero point and the gradient are performed with precision weights that are calibrated by an accredited calibration laboratory or an NMI.

Piston gauges with loaded piston

This kind of primary standard does not measure the pressure. Its piston is loaded with weights that are calibrated by an accredited calibration laboratory or an NMI. Due to the absence of a dynamometer, this kind of pressure gauge is a fundamental gauge with the lowest possible uncertainty. It is directly traceable to SI units of mass, length, temperature and time.

The pressure is generated by, and its value derived from, the known mass of the piston and the weights, the local gravity and the temperature-corrected effective area (A in Figure 3.1). To determine the measurement uncertainty, among other contributions to the uncertainty budget, the uncertainty of these three components must be known. Special attention must be given to the local gravity and its uncertainty. It is necessary that this local gravity (at the location of the standard) is determined by qualified personnel or accredited services. Note that the building in which the standard operates will affect the local gravity. See also Annex 3.B on the use of gravimeters.

A pressure controller is needed to raise the weights. At a certain height the piston is accelerated by a temporarily connected belt which is driven by a motor. At a certain rotation speed the belt is disconnected and the motor stops. Due to the extremely low friction of the nitrogen molecules the rotation speed will decelerate very slow. Depending on the amount of weights the rotation can persist up to a half an hour.

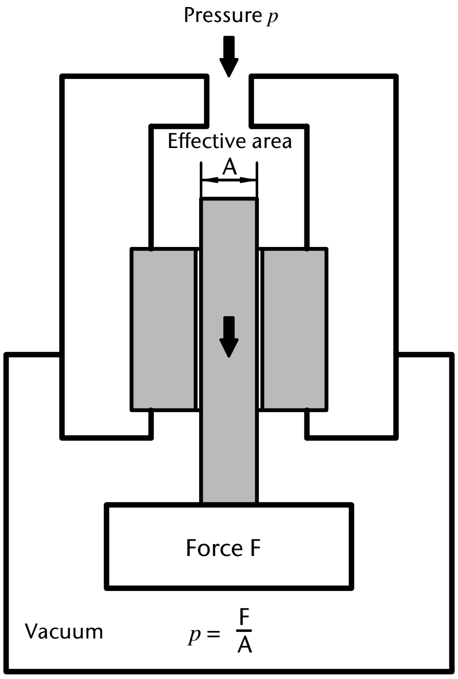

Figure 3.1. Piston gauge with dynamometer

If the piston rotates, the height of the piston vary slightly. To bring the piston back to a specific height, the pressure controller regulates the pressure below the piston area. Then, the pressure controller becomes inactive and its valves close. The pressure in the area below the piston and the connected pressure hose is generated by the rotating and very slowly sinking piston (Figure 3.2).

The area above the piston–cylinder system is covered with a glass bell. The bell is evacuated using a strong vacuum pump. The vacuum is measured with a vacuum gauge. The residual pressure has to be taken into account by the piston gauge controller.

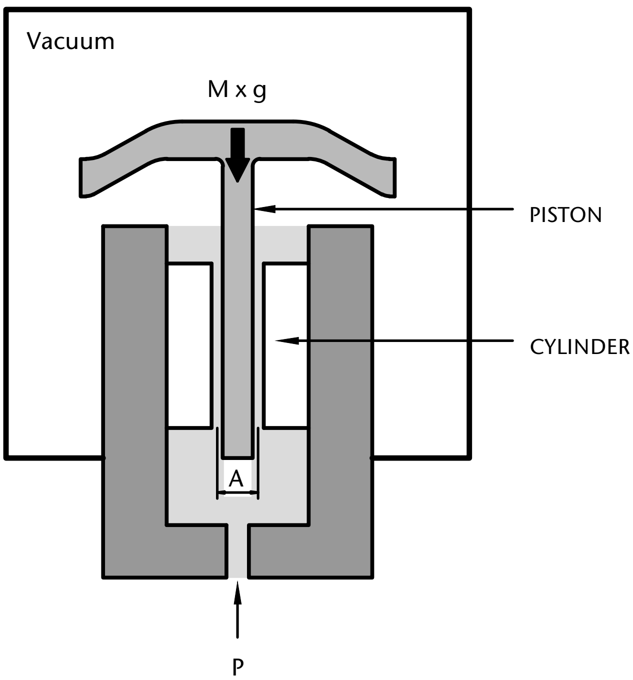

Figure 3.2. Loaded piston gauge

A disadvantage of piston gauges is the exchange of the weights. The evacuated area must be pressurized and the glass bell must be removed to change the weights. After reinstalling the glass bell the area must be evacuated again. The work with piston gauges is very time-consuming, but an automatic mass handling system is available for some types of piston gauges. Note that this technique requires well-trained personnel.

3.6.2.3 ***Method of calibration***

To achieve the required expanded measurement uncertainty, a comprehensive calibration procedure should be performed. Several guidelines are available. The following describes a proven procedure that is commonly used by accredited laboratories. It allows the evaluation of linearity, repeatability and reversibility.

The pressure range for calibration can be chosen either from 0% to 100% of the full scale of the instrument, or the interval can be reduced based on a client's requirements (for example, the range to be expected in operational use, such as 850–1050 hPa). Figure 3.3 shows the general calibration process.

The calibration process starts with generating maximum and minimum calibration points, sequentially, three times. The preloading time at the highest value and the time between two preloadings should be at least 30 seconds. The change of the pressure should be realized in 30 seconds and at least 120 seconds of holding time is needed.

The calibration should then be carried out at calibration points uniformly distributed over the calibration range. A cycle of measurements, each consisting of a series of increasing pressure and a series of decreasing pressure, must be taken. The number of points a series consists of should not be less than nine. The time between two successive load steps should be the same and not shorter than 30 seconds. At each calibration point, the waiting time, during which steady-state conditions are achieved, should be at least 120 seconds.

The mounting and connections should stay unchanged during the whole process.

The determination of the zero point deviation is usually omitted in the case of absolute pressure gauges, such as barometers, and consequently a zero-point adjustment is not performed.

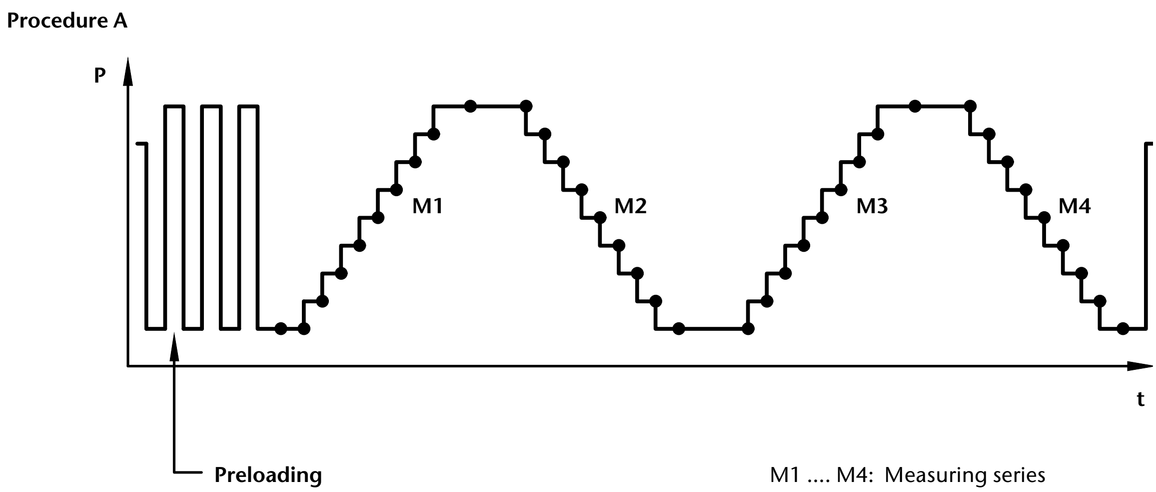

Figure 3.3. Calibration procedure

3.6.2.3.1 Calculation of repeatability

The repeatability is calculated from the difference between the deviations measured in the corresponding measurement series. The index *j* represents the nominal pressure point:

$$b_{up,j} = \left|\Delta p_{3,j} - \Delta p_{1,j}\right|$$

$$b_{down,j} = \left|\Delta p_{4,j} - \Delta p_{2,j}\right|$$

$$b_{mean,j} = max\left\{b_{up,j}, b_{down,j}\right\}$$

The repeatability must be considered for the calculation of the uncertainty.

Example:

Reference (hPa)	*Series 1 Δp (hPa)*	*Series 2 Δp (hPa)*	*Series 3 Δp (hPa)*	*Series 4 Δp (hPa)*
996.371	-0.002	0.008	0.001	0.007

$$b_{up,j} = \left|0.001\,hPa - \left(-0.002\,hPa\right)\right| = 0.003\,hPa$$

$$b_{down,j} = \left|0.007\,hPa - 0.008\,hPa\right| = 0.001\,hPa$$

$$b_{mean,j} = max\left\{0.003\,hPa,\, 0.001\,hPa\right\} = 0.003\,hPa$$

3.6.2.3.2 *Calculation of reversibility (hysteresis)*

The reversibility (hysteresis) is calculated from the differences between the corresponding deviations of the output values measured at increasing and decreasing pressure:

$$h_{mean,j} = \frac{1}{4}\left\{\left|\Delta p_{2,j} - \Delta p_{1,j}\right| + \left|(\Delta p_{4,j} - \Delta p_{3,j}\right|\right\}$$

The reversibility must be considered for the calculation of the uncertainty.

Example:

Reference (hPa)	*Series 1 Δp (hPa)*	*Series 2 Δp (hPa)*	*Series 3 Δp (hPa)*	*Series 4 Δp (hPa)*
996.371	-0.002	0.008	0.001	0.007

$$h_{mean,j} = \frac{1}{4}\left\{\left|0.008\,hPa - \left(-0.002\,hPa\right)\right| + \left|\left(0.007\,hPa - 0.001\,hPa\right)\right|\right\} = 0.004\,hPa\,.$$

3.6.3 Field inspections

During field inspection, a comparison with a travelling standard should be carried out.
This comparison is not a calibration, as in most cases just a one-point comparison at actual atmospheric pressure is performed. These checks can therefore only indicate the plausibility of the readings of the instrument on-site.

For field inspections, a mobile electronic pressure gauge, preferably with more than one pressure transducer, should be used as a travelling standard (see 3.2). With an appropriate temperature compensation, an uncertainty of 0.1 hPa or less can be achieved. Instruments with rechargeable batteries are available and the values from the internal transducers can be displayed separately or as a mean value. Before comparison, the instrument should always be acclimated to ambient conditions.

Field inspections should be performed in low gradient weather conditions with stable atmospheric pressure and low wind speeds.

Field inspection equipment should be calibrated by an accredited calibration laboratory, preferably before and after field use, or at appropriate calibration intervals, depending on the drift of the equipment.

3.7 ADJUSTMENT OF BAROMETER READINGS TO STANDARD AND OTHER LEVELS

To compare barometer readings taken at stations at different altitudes, it is necessary to reduce them to the same level. Whereas various methods are in use for carrying out this reduction, WMO has recommended a standard method described in the following paragraphs.

The recommended method is described in more detail in WMO (1954, 1964,1968). WMO (1966) contains a comprehensive set of formulae that may be used for calculations involving pressure.

3.7.1 Standard levels

The observed atmospheric pressure should be reduced to MSL (see the present volume, Chapter 1) for all stations where this can be done with reasonable accuracy. Where this is not possible, a station should, by regional agreement, report either the geopotential of an agreed "constant pressure level" or the pressure reduced to an agreed datum for the station. The level chosen for each station should be reported to the WMO Secretariat for promulgation (that is, the WMO Observing Systems Capability Analysis and Review Tool (OSCAR)/Surface, https://oscar.wmo.int/surface).

3.7.2 General reduction formula

Reduction formula for sea-level pressure feasible for stations below 750 m (from WMO, 1964, p. 22, equation 2):

$$\log_{10}\frac{p_0}{p_s} = \frac{K_p \cdot H_p}{T_{mv}} = \frac{K_p \cdot H_p}{T_s + \frac{a \cdot H_p}{2} + e_s \cdot C_h} \qquad (3.1)$$

where p_0 is the pressure reduced to sea level in hPa; p_S is the station pressure in hPa; K_p is the constant = 0.0148275 K gpm^{-1}; H_p is the station elevation in gpm; T_{mv} is the mean virtual temperature of the fictitious air column below station level in K, ($T_{mv} = T_S + (a \cdot H_p)/2 + e_S \cdot C_h$); T_S is the station temperature in K, $T_S = 273.15 + t$; t is the station temperature in °C; a is the assumed lapse-rate in the fictitious air column extending from sea level to the station elevation level = 0.0065 K gpm^{-1}; e_S is the vapour pressure at the station in hPa; and C_h is the coefficient = 0.12 K hPa^{-1}.

The same formula is often used in the exponential form:

$$p_0 = p_s \cdot \exp\left(\frac{\frac{g_n}{R} \cdot H_p}{T_s + \frac{a \cdot H_p}{2} + e_s \cdot C_h}\right) \qquad (3.2)$$

where g_n is the standard acceleration of gravity = 9.80665 m s^{-2} and R is the gas constant of dry air = 287.05 J kg^{-1} K^{-1}.

3.7.3 Reduction formula for low-level stations

At low-level stations (namely, those at a height of less than 50 m above MSL), pressure readings should be reduced to MSL by adding to the station pressure a reduction constant C given by the following expression:

$$C = p \cdot H_p / (29.27\, T_v) \tag{3.3}$$

where p is the observed station pressure in hectopascals; H_p is the station elevation in metres; and T_v is the mean annual normal value of virtual temperature at the station in K.

Note: The virtual temperature of damp air is the temperature at which dry air of the same pressure would have the same density as the damp air. WMO (1966) contains virtual temperature increments of saturated moist air for various pressures and temperatures.

This procedure should be employed only at stations of such low elevation that when the absolute extreme values of virtual temperature are substituted for T_v in the equation, the deviation of the result due to the other approximations of the equation (used for height rather than standard geopotential, and with C to be small compared with p) is negligible in comparison.

ANNEX 3.A. METHODS OF MEASUREMENT WITH MERCURY BAROMETERS

As outlined in 3.1.4.5, the use of mercury barometers is not recommended anymore. The reasons to move away from their use are: mercury vapour is highly toxic; free mercury is corrosive to the aluminium alloys used in air; special lead glass is required for the tube; the barometer is very delicate and difficult to transport; it is difficult to maintain the instrument and to clean the mercury; the instrument must be read and corrections applied manually; and other barometers of equivalent accuracy and stability with electronic read-out are now commonly available.

This annex is kept for information only.

1. UNITS AND SCALES

Some barometers are graduated in "millimetres or inches of mercury under standard conditions", $(\text{mm Hg})_n$ and $(\text{in Hg})_n$, respectively. When it is clear from the context that standard conditions are implied, the briefer terms "millimetre of mercury" or "inch of mercury" may be used. Under these standard conditions, a column of mercury having a true scale height of 760 $(\text{mm Hg})_n$ exerts a pressure of 1 013.250 hPa.

The following conversion factors will then apply:

$$1\ \text{hPa} = 0.750062\ (\text{mm Hg})_n$$
$$1\ (\text{mm Hg})_n = 1.333224\ \text{hPa}$$

In the case where the conventional engineering relationship between the inch and the millimetre is assumed, namely 1 in = 25.4 mm, the following conversion factors are obtained:

$$1\ \text{hPa} = 0.029530\ (\text{in Hg})_n$$
$$1\ (\text{in Hg})_n = 33.8639\ \text{hPa}$$
$$1\ (\text{mm Hg})_n = 0.03937008\ (\text{in Hg})_n$$

Scales on mercury barometers for meteorological purposes should be so graduated that they yield true pressure readings directly in standard units when the entire instrument is maintained at a standard temperature of 0 °C and the standard value of gravity is 9.80665 m s^{-2}.

Barometers may have more than one scale engraved on them, for example, hPa and mm Hg, or hPa and in Hg, provided that the barometer is correctly calibrated, adjusted and compensated for use under standard conditions.

2. REQUIREMENTS FOR MERCURY BAROMETERS

2.1 Construction requirements

The basic principle of a mercury barometer is that the pressure of the atmosphere is balanced against the weight of a column of mercury. In some barometers, the mercury column is weighed on a balance, but, for normal meteorological purposes, the length of the mercury column is measured against a scale graduated in units of pressure.

There are several types of mercury barometers in use at meteorological stations, with the fixed cistern and the Fortin types being the most common. The length to be measured is the distance between the top of the mercury column and the upper surface of the mercury in the cistern. Any change in the length of the mercury column is, of course, accompanied by a change in the level of the mercury in the cistern. In the Fortin barometer, the level of the mercury in the cistern can be adjusted to bring it into contact with an ivory pointer, the tip of which is at the zero of the barometer scale. In the fixed-cistern barometer, often called the Kew-pattern barometer, the mercury in the cistern does not need to be adjusted as the scale engraved on the barometer is constructed to allow for changes in the level of the mercury in the cistern.

2.2 **General requirements**

The main requirements of a good mercury station barometer include the following:

(a) Its accuracy should not vary over long periods. In particular, its hysteresis effects should remain small;

(b) It should be quick and easy to read, and readings should be corrected for all known effects. The observers employing these corrections must understand their significance to ensure that the corrections applied are correct and not, in fact, causing a deterioration in the accuracy of the readings;

(c) It should be transportable without a loss of accuracy;

(d) The bore of the tube should not be less than 7 mm and should preferably be 9 mm;

(e) The tube should be prepared and filled under vacuum. The purity of the mercury is of considerable significance. It should be double-distilled, degreased, repeatedly washed, and filtered;

(f) The actual temperature, for which the scale is assumed to give correct readings, at standard gravity, should be engraved upon the barometer. The scale should preferably be calibrated to give correct readings at 0 °C;

(g) The meniscus should not be flat unless the bore of the tube is large (greater than 20 mm);

(h) For a marine barometer, the error at any point should not exceed 0.5 hPa.

The response time for mercury barometers at land stations is usually very small compared with that of marine barometers and instruments for measuring temperature, humidity and wind.

2.3 **Exposure of mercury barometers**

The general exposure requirements of mercury barometers have been outlined in the preceding sections. Mercury barometers have additional exposure requirements above those already mentioned. It is always preferable to hang the mercury barometer on an inside wall. For very accurate work, the best position would be in an unheated basement room with no windows and with a small electric fan to prevent any stratification of temperature.

In order to obtain uniform lighting conditions for reading the barometer, it is advisable to use artificial lighting for all observations. For this purpose, some sort of illuminator – which can provide a white and slightly luminous background for the mercury meniscus and, if necessary, for the fiducial point – may be provided. If no illuminator is used, care should be taken to provide the meniscus and the fiducial point with a light background, by such means as pieces of milk glass, white celluloid, or a sheet of white paper. Artificial light should also be provided for reading the barometer scale and the attached thermometer. Care should, however, be taken to guard against heating the barometer with artificial light during a barometer reading.

The barometer should be mounted in a place where it is not subject to vibration, preferably on a solid wall. The instrument must be mounted with the mercury column in a vertical position. Errors due to departure from verticality are more critical for asymmetric barometers. Such barometers should be mounted with their longest axis vertical in order that a true setting of the mercury surface to the fiducial point remains correct even when the instruments are tilted from the vertical.

To protect the barometer from rough handling, dust and air currents, it is recommended that the instrument be placed in a box furnished with a hinged door with provisions for sufficient ventilation to prevent stratification of the air inside.

Great care should be taken when transporting a mercury barometer. The safest method is to carry the barometer upside down in a wooden case furnished with a sling. If the barometer cannot be accompanied by a responsible person, it ought to be transported in a suitable sprung crate with the cistern uppermost. The barometer should not be subject to violent movements and must always be turned over very slowly. Special precautions must be taken for some individual types of barometers before the instrument is turned over.

3. MEASUREMENTS USING MERCURY BAROMETERS

3.1 Standard conditions

Given that the length of the mercury column of a barometer depends on other factors, especially on temperature and gravity, in addition to the atmospheric pressure, it is necessary to specify the standard conditions under which the barometer should theoretically yield true pressure readings. The following standards are laid down in the international barometer conventions.

3.1.1 *Standard temperature and density of mercury*

The standard temperature to which mercury barometer readings are reduced to remove errors associated with the temperature-induced change in the density of mercury is 0 °C.

The standard density of mercury at 0 °C is taken to be $1.35951 \cdot 10^4$ kg m^{-3} and, for the purpose of calculating absolute pressure using the hydrostatic equation, the mercury in the column of a barometer is treated as an incompressible fluid.

The density of impure mercury is different from that of pure mercury. Hence, a barometer containing impure mercury will produce reading errors as the indicated pressure is proportional to the density of mercury.

3.1.2 *Standard gravity*

Barometric readings have to be reduced from the local acceleration of gravity to standard (normal) gravity. The value of standard gravity (g_n) is regarded as a conventional constant, $g_n = 9.80665$ m s^{-2}.

Note: The need to adopt an arbitrary reference value for the acceleration of gravity is explained in WMO (1966). This value cannot be precisely related to the measured or theoretical value of the acceleration of gravity in specified conditions, for example, sea level at latitude 45°, because such values are likely to change as new experimental data become available.

3.2 Reading mercury barometers

When making an observation with a mercury barometer, the attached thermometer should be read first. This reading should be taken as quickly as possible, as the temperature of the thermometer may rise owing to the presence of the observer. The barometer should be tapped a few times with the finger in two places, one adjacent to the meniscus and the other near the cistern, so as to stabilize the mercury surfaces. If the barometer is not of a fixed-cistern type, the necessary adjustment should be made to bring the mercury in the cistern into contact with the fiducial pointer. Lastly, the vernier should be set to the meniscus and the reading taken. The vernier is correctly adjusted when its horizontal lower edge appears to be touching the highest part of the meniscus; with a magnifying glass it should be possible to see an exceedingly narrow strip of light between the vernier and the top of the mercury surface. Under no circumstances should the vernier "cut off" the top of the meniscus. The observer's eye should be in such a position that both front and back lower edges of the vernier are in the line of vision.

3.2.1 *Accuracy of readings*

The reading should be taken to the nearest 0.1 hPa. Usually it is not possible to read the vernier to any greater accuracy.

Optical and digital systems have been developed to improve the reading of mercury barometers. Although they normally ease the observations, such systems may also introduce new sources of error, unless they have been carefully designed and calibrated.

3.2.2 *Changes in index correction*

Any change in the index correction shown during an inspection should be considered on its merits, keeping in mind the following:

(a) The history of the barometer;

(b) The experience of the inspector in comparison work;

(c) The magnitude of the observed change;

(d) The standard deviation of the differences;

(e) The availability of a spare barometer at the station, the correction of which is known with accuracy;

(f) The behaviour of travelling standards during the tour;

(g) The agreement, or otherwise, of the pressure readings of the station with those of neighbouring stations on the daily synoptic chart if the change is accepted;

(h) Whether or not the instrument was cleaned before comparison.

Changes in index errors of station barometers, referred to as drift, are caused by:

(a) Variations in the capillary depression of the mercury surfaces due to contamination of the mercury. In areas of severe atmospheric pollution from industrial sources, mercury contamination may constitute a serious problem and may require relatively frequent cleaning of the mercury and the barometer cistern;

(b) The rise of air bubbles through the mercury column to the space above.

These changes may be erratic, or consistently positive or negative, depending on the cause.

Changes in index correction are also caused by:

(a) Observer error resulting from failure to tap the barometer before taking the reading and improper setting of the vernier and fiducial point;

(b) Lack of temperature equilibrium in either the station barometer or the travelling standard;

(c) Non-simultaneity of readings when the pressure is changing rapidly.

Such changes can be caused by accidental displacement of the adjustable scale and the shrinkage or loosening of fiducial points in Fortin-type barometers.

3.2.3 *Permissible changes in index correction*

Changes in index correction should be treated as follows:

(a) A change in correction within 0.1 hPa may be neglected unless persistent;

(b) A change in correction exceeding 0.1 hPa but not exceeding 0.3 hPa may be provisionally accepted unless confirmed by at least one subsequent inspection;

(c) A change in correction exceeding 0.3 hPa may be accepted provisionally only if the barometer is cleaned and a spare barometer with known correction is not available. This barometer should be replaced as soon as a correctly calibrated barometer becomes available.

Barometers with changes in index correction identified in (b) and (c) above warrant close attention. They should be recalibrated or replaced as soon as practicable.

The same criteria apply to changes in the index corrections of the travelling standards as those applied as to station barometers. A change in correction of less than 0.1 hPa may be neglected unless persistent. A larger change in correction should be confirmed and accepted only after repeated comparisons. The "before" and "after" tour index corrections of the travelling standard should not differ by more than 0.1 hPa. Only barometers with a long history of consistent corrections should, therefore, be used as travelling standards.

3.3 Correction of barometer readings to standard conditions

In order to transform barometer readings taken at different times and different places into usable atmospheric pressure values, the following corrections should be made:

(a) Correction for index error;

(b) Correction for gravity;

(c) Correction for temperature.

For a large number of operational meteorological applications, it is possible to obtain acceptable results by following the barometer manufacturer's instructions, provided that it is clear that these procedures give pressure readings of the required uncertainty. However, if these results are not satisfactory or if higher precision is required, detailed procedures should be followed to correct for the above factors; these procedures are described in Annex 3.B.

3.4 Errors and faults with mercury barometers

3.4.1 *Uncertainties as to the temperature of the instrument*

The temperature indicated by the attached thermometer will not usually be identical to the mean temperature of the mercury, the scale and the cistern. The resultant error can be reduced by favourable exposure and by using a suitable observation procedure. Attention is drawn to the frequent existence of a large, stable vertical temperature gradient in a room, which may cause a considerable difference between the temperature of the upper and lower parts of the barometer. An electric fan can prevent such a temperature distribution but may cause local pressure variations and should be switched off before an observation is made. Under normal conditions, the error associated with the temperature reduction will not exceed 0.1 hPa if such precautions are taken.

3.4.2 *Defective vacuum space*

It is usually assumed that there is a perfect vacuum, or only a negligible amount of gas, above the mercury column when the instrument is calibrated. Any change in this respect will cause an error in pressure readings. A rough test for the presence of gas in the barometer tube can be made by tilting the tube and listening for the click when the mercury reaches the top, or by examining the closed end for the presence of a bubble, which should not exceed 1.5 mm in diameter when the barometer is inclined. The existence of water vapour cannot be detected in this way, as it is condensed when the volume decreases. According to Boyle's Law, the error caused by air and unsaturated water vapour in the space will be inversely proportional to the volume above the mercury. The only satisfactory way to overcome this error is by conducting a recalibration over the entire scale; if the error is large, the barometer tube should be refilled or replaced.

3.4.3 *The capillary depression of the mercury surfaces*

The height of the meniscus and the capillary depression[1], for a given tube, may change with the ageing of the glass tube, mercury contamination, pressure tendency, and the position of the mercury in the tube. As far as is practicable, the mean height of the meniscus should be observed during the original calibration and noted on the barometer certificate. No corrections should be made for departures from the original meniscus height, and the information should be used only as an indication of the need, or otherwise, to overhaul or recalibrate the barometer. A 1 mm change in the height of the meniscus (from 1.8 to 0.8 mm) for an 8 mm tube may cause an error of about 0.5 hPa in the pressure readings.

It should be noted that large variations in the angle of contact between the mercury and the wall of the cistern in a fixed-cistern barometer may cause small but appreciable errors in the observed pressure.

3.4.4 *Lack of verticality*

If the bottom of a symmetrical barometer of normal length (about 90 cm), which hangs freely, is displaced by about 6 mm from the vertical position, the indicated pressure will be about 0.02 hPa too high. Such barometers generally hang more truly vertical than this.

In the case of an asymmetrical barometer, however, this source of error is more critical. For example, if the fiducial pointer in the cistern is about 12 mm from the axis, the cistern needs to be displaced by only about 1 mm from the vertical to cause an error of 0.02 hPa.

[1] Capillary depression is a reduction in height of the meniscus of a liquid contained in a tube where the liquid (such as mercury) does not wet the walls of the tube. The meniscus is shaped convex upward.

3.4.5 *General accuracy of the corrected pressure readings*

The standard deviation of a single, corrected barometer reading at an ordinary meteorological station should be within 0.1 hPa. This error will mainly be the result of the unavoidable uncertainty in the instrument correction, the uncertainty concerning the temperature of the instrument, and the error caused by the pumping effect of wind gusts on the mercury surface.

4. SAFETY PRECAUTIONS FOR THE USE OF MERCURY

Mercury is used in relatively large quantities in barometers and, because it is poisonous, must be handled with care. Elemental mercury is a liquid at temperatures and pressures experienced at the Earth's surface. Mercury vapour forms in the air whenever liquid mercury is present. Mercury can be absorbed through the skin in both liquid and gaseous states and can be inhaled as a vapour. The properties of mercury are described by Sax (1975). In many countries, precautions for its use are prescribed by regulations governing the handling of hazardous goods. The UNEP Minamata Convention on Mercury entered into force in August 2017 and has a significant impact on the use of mercury for meteorological applications.

A large dose of mercury may cause acute poisoning. It can also accumulate in the body's hard and soft tissues and prolonged exposure to even a low dose can cause long-term damage to organs, or even death. Mercury mainly affects the central nervous system, and the mouth and gums, with symptoms that include pain, loosening of teeth, allergic reactions, tremors and psychological disturbance.

For barometric applications, the main risks occur in laboratories where barometers are frequently emptied or filled. There may also be problems in meteorological stations if quantities of mercury, for example from a broken barometer, are allowed to remain in places where it may continuously vaporize into an enclosed room where people work.

A danger exists even if the mercury is properly contained and if it is cleaned up after an accident. The following points must be considered when using mercury:

(a) Vessels containing mercury must be well sealed and not likely to leak or easily break, and must be regularly inspected;

(b) The floor of a room where mercury is stored or used in large quantities should have a sealed, impervious and crack-free floor covering, such as PVC. Small cracks in the floor, such as those between floor tiles, will trap mercury droplets. It is preferable to have the flooring material curving up the walls by approximately 10 cm, leaving no joint between the floor and the walls at floor level;

(c) Mercury must not be stored in a metal container as it reacts with almost all metals, except iron, forming an amalgam which may also be hazardous. Mercury should not come into contact with any other metallic object;

(d) Mercury must not be stored with other chemicals, especially amines, ammonia or acetylene;

(e) Large quantities of mercury should always be stored and handled in a well-ventilated room. The raw material should be handled in a good-quality fume cupboard;

(f) Mercury should never be stored near a heat source of any kind as it has a relatively low boiling point (357 °C) and may produce hazardous concentrations of toxic vapour, especially during a fire;

(g) If mercury is handled, the room where it is used and the personnel using it should be regularly tested to determine if hazardous quantities of mercury are being encountered.

Under the Minamata Convention, imports and exports of mercury will no longer be allowed. In this context, the production, import and export of mercury-added products such as thermometers will be stopped by 2020. The Convention (Article 4) states that "Each party shall not allow, by taking appropriate measures, the manufacture, import or export of mercury-added products listed in Part I of Annex A [of the Convention] after the phase-out date specified for those products" (UNEP, 2013). More specifically, this list includes (citation):

> The following non-electronic measuring devices except non-electronic measuring devices installed in large-scale equipment or those used for high precision measurement, where no suitable mercury-free alternative is available:
>
> (a) barometers;
>
> (b) hygrometers;
>
> (c) manometers;
>
> (d) thermometers;
>
> (e) sphygmomanometers.

4.1 Spillages and disposal

The two common methods of cleaning up mercury spillages are either with a suitable aspirated pick-up system, as outlined below, or by adsorption/amalgamation of the mercury onto a powder.

Mercury should be cleaned up immediately. The operator should wear PVC gloves or gauntlets, safety goggles and, for significant spills, a respirator fitted with a mercury vapour cartridge. Depending upon how large the spillage is, the mercury will be picked up by using a vacuum system; an adsorption kit should then be used to clean up the small droplets. The use of an adsorption kit is imperative because, during a spillage, dozens of small droplets of less than 0.02 mm in diameter will adhere to surfaces and cannot be efficiently removed with a vacuum system.

In an aspirated pick-up system, the mercury is drawn through a small-diameter plastic tube into a glass flask with approximately 3 cm of water in the bottom, with the tube opening being below the water line in the flask. One end of a larger diameter plastic tube is connected to the air space above the water in the flask, and the other end is connected to a vacuum cleaner or vacuum pump. The water prevents the mercury vapour or droplets from being drawn into the vacuum cleaner or pump. The slurry is then placed in a clearly labelled plastic container for disposal.

By using adsorption material, a variety of compounds can be used to adsorb or amalgamate mercury. These include zinc powder, sulphur flour or activated carbon. Commercial kits are available for cleaning up mercury spills. The powder is sprinkled on the spill and allowed to adsorb or amalgamate the mercury. The resulting powder is swept up and placed in a clearly labelled plastic container for disposal.

The collected mercury can be either disposed of or recovered. Details on how to dispose of mercury can be obtained from local authorities and/or the supplier. The supplier can also advise on recovery and purification.

4.2 Fire

Mercury will not burn but does give off significant concentrations of toxic fumes. After a fire, the mercury vapour will condense on the nearest cool surfaces, contaminating large areas and being adsorbed onto open surfaces, such as carbonized timber. During a fire, evacuate the area and remain upwind of any fumes. Advise the fire authorities of the location and quantity of mercury involved.

4.3 Transportation

The transportation by air of mercury or instruments containing mercury is regulated by the International Air Transport Association. Airlines will provide the specific conditions for such transport upon request. Transportation by rail or road is usually governed by the hazardous material regulations in each country.

In general, metallic mercury must be packed in glass or plastic containers. The containers should be packed with sufficient cushioning to prevent breakage and should be clearly labelled. Mercury-containing instruments should be packed in a strong cushioned case which is leak-proof and impervious to mercury.

ANNEX 3.B. CORRECTION OF MERCURY BAROMETER READINGS TO STANDARD CONDITIONS

Correction for index error

The residual errors in the graduation of the scale of a barometer should be determined by comparison with a standard instrument. They may include errors due to inaccurate positioning or subdividing of the scale, capillarity and imperfect vacuum. Certificates of comparison with the standard should state the corrections to be applied for index error at no fewer than four points of the scale, for example, at every 50 hPa. In a good barometer, these corrections should not exceed a few tenths of a hectopascal.

Corrections for gravity

The reading of a mercury barometer at a given pressure and temperature depends upon the value of gravity, which in turn varies with latitude and altitude. Barometers for meteorological applications are calibrated to yield true pressure readings at the standard gravity of 9.80665 m s^{-2} and their readings at any other value of gravity must be corrected. The following method is recommended for reducing such barometer readings to standard gravity. Let B be the observed reading of the mercury barometer, B_t the barometer reading reduced to standard temperature but not to standard gravity, and corrected for instrumental errors, B_n be the barometer reading reduced to standard gravity and standard temperature, and corrected for instrumental errors, B_{ca} be the climatological average of B_t at the station, $g_{\varphi H}$ the local acceleration of gravity (in m s^{-2}) at a station at latitude φ and elevation H above sea level, and g_n the standard acceleration of gravity, 9.80665 m s^{-2}.

The following relations are appropriate:

$$B_n = B_t \left(g_{\varphi H} / g_n \right) \tag{3.A.1}$$

or:

$$B_n = B_t + B_t \left[\left(g_{\varphi H} / g_n \right) - 1 \right] \tag{3.A.2}$$

The approximate equation 3.A.3 may be used, provided that the results obtained do not differ by more than 0.1 hPa from the results that would be obtained with the aid of equation 3.A.2:

$$B_n = B_t + B_{ca} \left[\left(g_{\varphi H} / g_n \right) - 1 \right] \tag{3.A.3}$$

The local acceleration of gravity $g_{\varphi H}$ should be determined by the procedure outlined in the following section. The values so derived should be referred to as being on the International Gravity Standardization Net 1971 (IGSN71).

Determining local acceleration of gravity

In order to determine the local value of the acceleration of gravity at a station to a satisfactory degree of precision, one of two techniques should be used. These techniques involve, in the first case, the use of a gravimeter (an instrument for measuring the difference between the values of the acceleration of gravity at two points) and, in the second case, the use of the so-called Bouguer anomalies. Preference should be given to the gravimeter method. If neither of these methods can be applied, the local acceleration of gravity may be calculated using a simple model of the Earth.

Use of a gravimeter

Suppose g_1 represents the known local acceleration of gravity at a certain point O, usually a gravity base station established by a geodetic organization, where g_1 is on the IGSN71, and suppose further that g represents the unknown local acceleration of gravity on the meteorological gravity system at some other point X for which the value g is desired. Let Δg denote the difference in gravity acceleration at the two places, as observed by means of a gravimeter. That is, Δg is the value at point X minus the value at point O on a consistent system. Then, g is given by equation 3.A.4:

$$g = g_1 + \Delta g \tag{3.A.4}$$

Use of Bouguer anomalies

If a gravimeter is not available, interpolated Bouguer anomalies (A_B) may be used to obtain g at a given point. It is necessary that a contour chart of these anomalies be available from a geodetic organization or from a network of gravity stations spaced at a density of at least one station per 10 000 km^2 (no more than a 100 km distance between stations) in the vicinity of the point.

Gravity networks of somewhat less density can be used as a basis provided that a geodetic organization considers that this method is expected to yield more reliable results than those that could be obtained by using a gravimeter.

The definition of the Bouguer anomaly (A_B) is derivable from equation 3.A.5:

$$g_s = \left(g_{\varphi,0}\right)s - C \cdot H + A_B \tag{3.A.5}$$

where $(g_{\varphi,0})s$ is the theoretical value of the acceleration of gravity at latitude φ at sea level, as given by the formula actually used in computing the Bouguer anomaly. This formula expresses the value as a function of latitude in some systems. H is the elevation of the station (in metres) above sea level at which g_s is measured, g_s is the observed value of the acceleration of gravity (in m s^{-2}); A_B is the Bouguer anomaly (in m s^{-2}); and C is the elevation correction factor used in computing the Bouguer anomaly (for example, using a crustal specific gravity of 2.67, this factor is 0.000001968 m s^{-2}).

When g is desired for a given station and has not been measured, the value of g_s should be computed by means of equation 3.A.5, provided that the appropriate value of A_B for the locality of the station can be interpolated from the aforementioned contour charts or from data representing the Bouguer anomalies supplied by a suitable network of gravity stations, as defined.

Calculating local acceleration of gravity

If neither of the preceding methods can be applied, the local value may be calculated less accurately according to a simple model. According to the Geodetic Reference System 1980, the theoretical value ($g_{\varphi,0}$) of the acceleration of gravity at MSL at geographic latitude, φ, is computed by means of equation 3.A.6:

$$g_{\varphi,0} = 9.806\,20\left(1 - 0.002\,644\,2\cos 2\varphi + 0.000\,005\,8\cos^2 2\varphi\right) \tag{3.A.6}$$

The local value of the acceleration of gravity at a given point on the surface of the ground at a land station is computed by means of equation 3.A.7:

$$g = g_{\varphi,0} - 0.000\,003\,086\,H + 0.000\,001\,118\left(H - H'\right) \tag{3.A.7}$$

where g is the calculated local value of the acceleration of gravity, in m s^{-2}, at a given point; $g_{\varphi,0}$ is the theoretical value of the acceleration of gravity in m s^{-2} at MSL at geographic latitude φ, computed according to equation 3.A.6 above; H is the actual elevation of the given point, in metres above MSL; and H' is the absolute value in metres of the difference between the height of the given point and the mean height of the actual surface of the terrain included within a circle whose radius is about 150 km, centred at the given point.

The local value of the acceleration of gravity at a given point within height H above MSL of not more than about 10 km, and where that point lies over the sea water surface, is computed by means of equation 3.A.8:

$$g = g_{\varphi,0} - 0.000\,003\,086\,H - 0.000\,006\,88\left(D - D'\right) \quad (3.A.8)$$

where D is the depth of water in metres below the given point; and D' is the mean depth of water, in metres, included within a circle whose radius is about 150 km centred at the given point.

At stations or points on or near the coast, the local value of acceleration of gravity should be calculated, so far as practicable, through the use of equations 3.A.7 and 3.A.8 on a pro rata basis, weighting the last term of equation 3.A.7 according to the relative area of land included within the specified circle, and weighting the last term of equation 3.A.8 according to the relative area of the sea included within the circle. The values thus obtained are then combined algebraically to obtain a correction which is applied to the final term in the right-hand side of both equations, as shown in equation 3.A.9:

$$g = g_{\varphi,0} - 0.000\,003\,086\,H + 0.000\,001\,118\,\alpha \left(H - H'\right) - 0.000\,006\,88\left(1 - \alpha\right)\left(D - D'\right) \quad (3.A.9)$$

where α is the fraction of land area in the specified area, and H' and D' refer to the actual land and water areas, respectively.

Corrections for temperature

Barometer readings must be corrected to the values that would have been obtained if the mercury and the scale had been at their standard temperatures. The standard temperature for mercury barometers is 0 °C. With reference to scales, some barometers have scales which read accurately at this same temperature, but some read accurately at 20 °C.

The temperature correction necessary for adjustable cistern barometers (Fortin-type barometers) is different from that required for fixed-cistern barometers, though the principle reasons leading to the necessity for temperature corrections are the same for both types, namely, the fact that the coefficient of cubic thermal expansion of mercury is different from the coefficient of linear thermal expansion of the scale. Thus, a certain correction term is required for both types of mercury barometer.

A fixed-cistern barometer requires an additional correction. The reason for this is that an increase in temperature of the instrument causes an increase both in the volume of the mercury and in the cross-sectional areas of the (iron) cistern and the (glass) tube. Owing to these area changes, the apparent rise of the mercury resulting from a temperature increase is less than would be the case if the areas remained constant. This is because some of the mercury from the barometer goes to occupy the capacity increment produced by the expansion of the cistern and tube.

The scale of a fixed-cistern barometer must, for a variety of reasons, undergo a calibration check against a primary standard barometer of the adjustable-cistern type. Some manufacturers decrease the volume of mercury by such an amount that the readings of the test barometer agree with the readings of the standard barometer at 20 °C. Correction tables can be generated for fixed-cistern barometers using the readings from a primary standard barometer whose scales are accurate when 20 °C is used as the reference temperature.

Temperature corrections for mercury barometers

Researchers have conducted exhaustive studies for temperature corrections for mercury barometers, the results of which are summarized below:

1 (a) Scale correct at 0 °C and additionally — $C_t = -B(\alpha - \beta) \cdot t$

(b) Hg volume correct at 0 ° — $C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot t \cdot 4V/3A$

2 Scale correct at 0 °C and Hg volume correct at 20 °C — $C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot (t - 20) \cdot 4V/3A$

3 (a) Scale correct at 20 °C — $C_t = -B[\alpha \cdot t - \beta \cdot (t - 20)]$

(b) Hg volume correct at 0 °C — $C_{t,V} = -B[\alpha \cdot t - \beta \cdot (t - 20)] - (\alpha - 3\eta) \cdot t \cdot (4V/3A)$

(c) Hg volume decreasing by an amount equivalent to 0.36 hPa — $C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot t \cdot (4V/3A)$

4 Scale correct at 20 °C and

(a) Hg volume correct at 20 °C — $C_{t,V} = -B[\alpha \cdot t - \beta(t - 20)] - (\alpha - 3\eta) \cdot (t - 20) \cdot (4V/3A)$

(b) Hg volume decreasing by an amount equivalent to 0.36 hPa — $C_{t,V} = -B(\alpha - \beta) \cdot t - (\alpha - 3\eta) \cdot (t - 20) \cdot (4V/3A)$

where:

C_t = temperature correction;

$C_{t,V}$ = additional correction for fixed-cistern barometers;

B = observed barometer reading;

V = total volume of mercury in the fixed-cistern barometer;

A = effective cross-sectional area of the cistern;

t = temperature;

α = cubic thermal expansion of mercury;

β = coefficient of linear thermal expansion of the scale;

η = coefficient of linear thermal expansion of the cistern.

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