CHAPTER 12 — MEASUREMENT OF UPPER AIR PRESSURE, TEMPERATURE, AND HUMIDITY

CHAPTER 12

MEASUREMENT OF UPPER AIR PRESSURE, TEMPERATURE, AND HUMIDITY

12.1 General

12.1.1 *Definitions*

The following definitions from WMO (1981; 1992) are relevant to upper air measurements using a radiosonde:

> *Radiosonde*: Instrument intended to be carried by a ballon through the atmosphere, equipped with devices to measure one or several meteorological variables (pressure, temperature, humidity, etc.), and provided with a radio transmitter for sending this information to the observing station.
>
> *Radiosonde observation*: An observation of meteorological variables in the upper air, usually atmospheric pressure, temperature and humidity, by means of a radiosonde.
>
> NOTE: The radiosonde may be attached to a balloon, or it may be dropped (dropsonde) from an aircraft or a rocket.
>
> *Radiosonde station*: A station at which observations of atmospheric pressure, temperature and humidity in the upper air are made by electronic means.
>
> *Upper air observation*: A meteorological observation made in the free atmosphere, either directly or indirectly.
>
> *Upper air station, upper air synoptic station, aerological station*: A surface location from which upper air observations are made.
>
> *Sounding*: Determination of one or several upper air meteorological variables by means of instruments carried aloft by balloon, aircraft, kite, glider, rocket, etc.

This chapter will primarily deal with radiosonde systems. Measurements using special platforms, specialized equipment, or made indirectly by remote sensing methods will be discussed in various chapters of Part II of this *Guide*. Radiosonde systems are normally used to measure pressure, temperature and relative humidity. At most operational sites, the radiosonde system is also used for upper-wind determination (see Chapter 13). In addition, some radiosondes are flown with sensing systems for atmospheric constituents, such as ozone concentration or radioactivity. These additional measurements are not discussed in any detail in this chapter.

12.1.2 *Units used in upper air measurements*

The units of measurement for the meteorological variables of radiosonde observations are the hectopascal for pressure, the degree Celsius for temperature, and per cent for relative humidity. Relative humidity is reported relative to saturated vapour pressure over a water surface, even at temperatures less than 0°C.

The unit of geopotential height used in upper air observations is the standard geopotential metre, defined as 0.980 665 dynamic metres. In the troposphere, the value of the geopotential height is approximately equal to the geometric height expressed in metres.

The values of the physical functions and constants adopted by WMO (WMO, 1988*b*) should be used in radiosonde computations.

12.1.3 *Meteorological requirements*

12.1.3.1 RADIOSONDE DATA FOR METEOROLOGICAL OPERATIONS

Upper air measurements of temperature and relative humidity are two of the basic measurements used in the initialization of the analyses of numerical weather prediction models for operational weather forecasting. Radiosondes provide most of the *in situ* temperature and relative humidity measurements over land, while radiosondes launched from remote islands or ships provide a limited coverage over the oceans. Temperatures with resolution in the vertical similar to radiosondes can be observed by aircraft either during ascent, descent, or at cruise levels. The aircraft observations are used to supplement the radiosonde observations, particularly over the sea. Satellite observations of temperature and water vapour distribution have lower vertical resolution than radiosonde or aircraft measurements. The satellite observations have greatest impact on numerical weather prediction analyses over the oceans and other areas of the globe where radiosonde and aircraft observations are sparse or unavailable.

Accurate measurements of the vertical structure of temperature and water vapour fields in the troposphere are extremely important for all types of forecasting, especially regional and local forecasting. The measurements indicate the existing structure of cloud or fog layers in the vertical. Furthermore, the vertical structure of temperature and water vapour fields determines the stability of the atmosphere and, subsequently, the amount and type of cloud that will be forecast. Radiosonde measurements of the vertical structure can usually be provided with sufficient accuracy to meet most user requirements. However, negative systematic errors in radiosonde relative humidity measurements of high humidity in clouds cause problems in numerical weather prediction analyses, if the error is not compensated.

High resolution measurements of the vertical structure in temperature and relative humidity are important for environmental pollution studies (for instance, identifying the depth of the atmospheric boundary layer). High resolution in the vertical is also necessary for forecasting the effects of atmospheric refraction on the propagation of electromagnetic radiation or sound waves.

Civil aviation, artillery and other ballistic applications, such as launches of space vehicles, have operational requirements for measurements of the density of air at given pressures (derived from radiosonde temperature and relative humidity measurements).

Radiosonde observations are vital for studies of upper air climate change. Hence, it is important to keep adequate records of the systems used for measurements and also of any changes in the operating or correction procedures used with the equipment. In this context, it has proved necessary to establish the changes in radiosonde instruments and practices that have taken place since radiosondes were used on a regular basis (see for instance WMO, 1993*a*). Climate change studies based on radiosonde measurements require extremely high stability in the systematic errors of the radiosonde measurements. However, the errors in early radiosonde measurements of some meteorological variables, particularly relative humidity and pressure, were too high to provide acceptable long-term references at all heights reported by the radiosondes. Thus, improvements and changes in radiosonde design were necessary. Furthermore, expenditure limitations on meteorological operations require that radiosonde consumables remain cheap if widespread radiosonde use is to continue. Therefore, certain compromises in system measurement accuracy have to be accepted by users, taking into account that radiosonde manufacturers are producing systems that need to operate over an extremely wide range of meteorological conditions:

1 050 to 5 hPa for pressure
50 to –90°C for temperature
100 to 1 per cent for relative humidity

with the systems being able to sustain continuous reliable operation when operating in heavy rain, the vicinity of thunderstorms, and in severe icing conditions.

12.1.3.2 RELATIONSHIPS BETWEEN SATELLITE AND RADIOSONDE UPPER AIR MEASUREMENTS

Satellite observing systems do not measure vertical structure with the same accuracy or degree of confidence as radiosonde or aircraft systems. The current satellite temperature and water vapour sounding systems either observe upwelling radiances from carbon dioxide or water vapour emission in the infrared, or alternatively oxygen or water vapour emission at microwave frequencies (see Chapter 8, of Part II). The radiance observed by a satellite channel is composed of atmospheric emission from a range of heights in the atmosphere. This range is determined by the distribution of emitting gases in the vertical and the atmospheric absorption at the channel frequencies. Most radiances from satellite temperature channels approximate mean layer temperatures for a layer at least 10-km thick. The height distribution (weighting function) of the observed temperature channel radiance will vary with geographical location to some extent. This is because the radiative transfer properties of the atmosphere have a small dependence on temperature. The concentrations of the emitting gas may vary to a small extent with location and cloud; aerosol and volcanic dust may also modify the radiative heat exchange. Hence, basic satellite temperature sounding observations provide good horizontal resolution and spatial coverage worldwide for relatively thick layers in the vertical, but the precise distribution in the vertical of the atmospheric emission observed may be difficult to specify at any given location.

Most radiances observed by satellite water vapour channels in the troposphere originate from layers of the atmosphere about 4 to 5-km thick. The pressures of the atmospheric layers contributing to the radiances observed by a water vapour channel vary with location to a much larger extent than for the temperature channels. This is because the thickness and central pressure of the layer observed depend strongly on the distribution of water vapour in the vertical. For instance, the layers observed in a given water vapour channel will be lowest when the upper troposphere is very dry. The water vapour channel radiances observed depend on the temperature of the water vapour, so water vapour distribution in the vertical can only be derived once suitable measurements of vertical temperature structure are available.

Thus, the techniques developed for using satellite sounding information in numerical weather prediction models incorporate information from other observing systems, mainly radiosondes and aircraft. This information may be contained in an initial estimate of vertical structure at a given location, which is derived from forecast model fields or is found in catalogues of possible vertical structure based on radiosonde measurements typical of the geographical location or air mass type. In addition, radiosonde measurements are used to cross-reference the observations from different satellites or the observations at different view angles from a given satellite channel. The comparisons may be made directly with radiosonde observations or indirectly through the influence from radiosonde measurements on the vertical structure of numerical forecast fields.

Hence, radiosonde and satellite sounding systems are complementary observing systems and provide a more reliable global observation system when used together.

12.1.3.3 MAXIMUM HEIGHT OF RADIOSONDE OBSERVATIONS

Radiosonde observations are used regularly for measurements up to heights of about 35 km. However, many observations worldwide will not be made to heights greater than about 25 km, because of the higher cost of the balloons and gas necessary to lift the equipment to the lowest pressures. Temperature errors in many radiosonde systems increase rapidly at low pressures, so that some of the available radiosonde systems are unsuitable for observing at the lowest pressures.

The problems associated with the contamination of sensors during flight and very long time constants of sensor response at low temperatures and pressures limit the usefulness of radiosonde relative humidity measurements to the troposphere.

12.1.3.4 ACCURACY REQUIREMENTS

This section and the next summarize the requirements for radiosonde accuracy and compare them with operational performance. A detailed discussion of performance and sources of errors is given in later sections.

The accuracy requirements for radiosonde observations are summarized in Annex 1.C of Chapter 1[1]. Annex 12.A is a slightly more detailed practical interpretation of these requirements, for guidance in routine operations.

WMO (1970) describes a very useful approach to the consideration of the performance of instrument systems, which has application on the system design. The performance is based on observed atmospheric variability. Two limits are defined:

(*a*) The limits of performance beyond which improvement is unnecessary for various purposes;

(*b*) The limit of performance below which the data obtained would be of negligible value for various purposes.

The performance limits derived by in WMO (1970) for upper wind and for radiosonde temperature, relative humidity and geopotential height measurements are contained in Tables 1 to 4 of Annex 12.B.

12.1.3.5 TEMPERATURE: REQUIREMENTS AND PERFORMANCE

Most modern radiosonde systems measure temperature in the troposphere with a standard error of between 0.2 and 0.5 K. This performance is usually within a factor of 3 of the optimum performance suggested in Table 2 of Annex 12.B. Unfortunately, standard errors larger than 1 K are still found in some radiosonde networks in tropical regions. The measurements at these stations fall outside the lower performance limit found in Table 2 of Annex 12.B, and are in the category where the measurements have negligible value for the stated purpose.

At pressures higher than about 30 hPa in the stratosphere, the measurement accuracy of most modern radiosondes is similar to the measurement accuracy in the troposphere. Thus, in this part of the stratosphere, radiosonde measurement errors are about twice the stated optimum performance limit. At pressures lower than 30 hPa, the errors in many radiosonde types increase rapidly with decreasing pressure and in some cases approach the limit where they cease to be useful for the stated purpose. The rapid escalation in radiosonde temperature measurement errors at very low pressure results from an increase in temperature errors associated with infrared and solar radiation coupled with a rapid increase in errors in the heights assigned to the temperatures. At very low pressures, even relatively small errors in the radiosonde pressure measurements will produce large errors in height and, hence, reported temperature (see section 12.1.3.7).

12.1.3.6 RELATIVE HUMIDITY

Errors in modern radiosonde relative humidity measurements are at least a factor of two or three larger than the optimum performance limit for high relative humidity suggested in Table 3 of Annex 12.B, for the troposphere above the convective boundary layer. Furthermore, the errors in radiosonde relative humidity measurements increase as temperature decreases. For some sensor types, errors at temperatures lower than –40°C may exceed the limit where the measurements have no value for the stated purpose.

12.1.3.7 GEOPOTENTIAL HEIGHTS

Errors in geopotential height determined from radiosonde observations differ according to whether the height is for a specified pressure level or for the height of a given turning point in the temperature or relative humidity structure, such as the tropopause.

The error, $\epsilon_z(t_1)$, in the geopotential height at a given time into flight is given by:

$$\epsilon_z(t_1) = \frac{R}{g} \int_{p_0}^{p_1} [\epsilon_T(p) - \frac{\delta T}{\delta p} \epsilon_p(p)] \frac{dp}{p} + \frac{R}{g} \int_{p_1}^{p_1 + \epsilon_p(p_1)} [T_v(p) + \epsilon_T(p) - \frac{\delta T}{\delta p} \epsilon_p(p)] \frac{dp}{p} \qquad (12.1)$$

where p_0 is the surface pressure; p_1 is the true pressure at time t_1; $p_1 + \epsilon_p(p_1)$ is the actual pressure indicated by the radiosonde at time t_1; $\epsilon_T(p)$ and $\epsilon_p(p)$ are the errors in the radiosonde temperature and pressure measurements, respectively, as a function of pressure; $T_v(p)$ is the virtual temperature at pressure p; and R and g are the gas and gravitational constants as specified in WMO (1988*b*).

For a specified standard pressure level, p_s, the pressure of the upper integration limit in the height computation is specified and is not subject to the radiosonde pressure error. Hence, the error in the standard pressure level geopotential height reduces to:

$$\epsilon_z(p_s) = \frac{R}{g} \int_{p_0}^{p_s} [\epsilon_T(p) - \frac{\delta T}{\delta p} \epsilon_p(p)] \frac{dp}{p} \qquad (12.2)$$

Table 12.1 shows, for typical atmospheres, the errors in geopotential height that are caused by radiosonde sensor errors. It shows that the geopotentials of given pressure levels can be measured quite well, which is convenient for the synoptic and numerical analysis of constant pressure surfaces. However, large

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[1] Adopted by the Commission for Basic Systems, at its extraordinary session (1994).

TABLE 12.1

Errors in geopotential height (m)

(Typical errors in standard levels ($\epsilon_z (p_s)$) and significant levels ($\epsilon_z(t_l)$) for given temperature and pressure errors, at or near specified levels. Errors are similar in northern and southern latitudes)

	300 hPa	*100 hPa*	*30 hPa*	*10 hPa*
Temperature error $\epsilon_T = 0.25$ K, pressure error $\epsilon_p = 0$ hPa				
Standard and significant levels	9	17	26	34
Temperature error $\epsilon_T = 0$ K, pressure error $\epsilon_p = -1$ hPa				
25°N				
Standard level	3	12	–2	–24
Significant level	27	72	211	650
50°N summer				
Standard level	3	5	1	–20
Significant level	26	72	223	680
50°N winter				
Standard level	3	5	6	–4
Significant level	26	70	213	625

errors may occur in the heights of significant levels such as the tropopause and other turning points, and other levels may be calculated between the standard levels.

Large height errors in the stratosphere resulting from pressure sensor errors of 2 or 3 hPa are likely to be of greatest significance in routine measurements in the tropics, where there are always significant temperature gradients in the vertical throughout the stratosphere. Ozone concentrations in the stratosphere also have pronounced gradients in the vertical and height assignment errors will introduce significant errors into the ozonesonde reports at all latitudes.

The optimum performance requirements for the heights of isobaric surfaces in a synoptic network, as stated in Table 4 of Annex 12.B, place extremely stringent requirements on radiosonde measurement accuracy. For instance, the best modern radiosondes would do well if height errors were only a factor of 5 higher than the optimum performance in the troposphere and an order of magnitude higher than the optimum performance in the stratosphere.

12.1.4 *Methods of measurement*

This section discusses radiosonde methods in general terms. Details of instrumentation and procedures are given in other sections.

12.1.4.1 CONSTRAINTS ON RADIOSONDE DESIGN

Certain compromises are necessary when designing a radiosonde. Temperature measurements are found to be most reliable when sensors are exposed unprotected above the top of the radiosonde, but this also leads to direct exposure to solar radiation. In most modern radiosondes, coatings are applied to the temperature sensor to minimize solar heating. Software corrections for the residual solar heating are then applied during data processing. This method of mounting temperature sensors has proved to be more reliable in practice than mounting the temperature sensor in a protective duct. Nearly all relative humidity sensors require some protection from rain. A protective cover or duct reduces the ventilation of the sensor and hence the speed of response of the sensing system as a whole. The cover or duct also provides a source of contamination after passing through cloud. However, in practice, the requirement for protection from rain or ice for relative humidity sensors is usually more important than perfect exposure to the ambient air. Thus, protective covers or ducts are usually used with a relative humidity sensor. Pressure sensors are usually mounted internally to minimize the temperature changes in the sensor during flight and to avoid conflicts with the exposure of the temperature and relative humidity sensors.

Other important features required in radiosonde design are reliability, robustness, small weight and small bulk. With modern electronic multiplexing readily available, it is also important to sample the radiosonde sensors at a high rate. If possible, this rate should be higher than once every 2 s, corresponding to a minimum sample separation of about 10 m in the vertical. Since a radiosonde is generally used only once, or not more than a few times, it must be designed for mass production at low cost. Ease and stability of calibration is very important, since radiosondes must often be stored for long periods (more than a year) prior to use.

A radiosonde should be capable of transmitting an intelligible signal to the ground receiver over a slant range of at least 200 km. The voltage of the radiosonde battery varies with both time and temperature. Therefore, the radiosonde must be designed to accept the battery variations without a loss of measurement accuracy or an unacceptable drift in the transmitted radiofrequency.

12.1.4.2 RADIOFREQUENCY USED BY RADIOSONDES

The radiofrequency spectrum bands currently used for most radiosonde transmissions are shown in Table 12.2. These correspond to the meteorological aids allocations specified by the ITU-R radio regulations.

TABLE 12.2

Primary frequencies used by radiosondes in the meteorological aids bands

Radiofrequency band (MHz)	*Status*	*ITU regions*
–5.85	Primary	All
–31.6	Primary	All

NOTE: Most secondary radar systems manufactured and deployed in Russia operate in a radiofrequency band centred at 1 780 MHz.

The radiofrequency actually chosen for radiosonde operations in a given location will depend on various factors. At sites where strong upper winds are common, slant ranges to the radiosonde are usually large and balloon elevations are often very low. Under these circumstances, the 400-MHz band will normally be chosen for use since a good communication link from the radiosonde to the ground system is more readily achieved at 400 MHz than at 1 680 MHz. When upper winds are not so strong, the choice of frequency will, on average, usually be determined by the method of upper wind measurement used (see Chapter 13). 400 MHz is usually used when NAVAID windfinding is chosen and 1 680 MHz when radiotheodolites are used for wind measurement.

The radiofrequencies listed in Table 12.2 are allocated on a shared basis with other services. In some countries, the national radiocommunication authority has allocated part of the bands to other users and the whole of the band is not available for radiosonde operations. In other countries, where large numbers of radiosonde systems are deployed in a dense network, there are stringent specifications on radiofrequency drift and bandwidth occupied by an individual flight.

Any organization proposing to fly radiosondes should check that suitable radiofrequencies are available for their use and should also check that they will not interfere with the radiosonde operations of the national Meteorological Service.

There are now strong pressures, supported by government radiocommunication agencies, to improve the efficiency of radiofrequency use. Therefore, radiosonde operations will have to share with a greater range of users in the future. Wideband radiosonde systems occupying most of the available spectrum of the meteorological aids bands may become impracticable in many countries. If proposals for operating satellite uplinks or downlinks to commercial data collection or paging systems in the meteorological aids bands are accepted, then wideband radiosonde system operations will become impractical all over the world. Therefore, preparations for the future in most countries should be based on the principle that radiosonde transmitters and receivers will have to work with bandwidths of much less than 1 MHz in order to avoid interfering signals. Transmitter stability may have to be better than ±5 kHz in countries with dense radiosonde networks and not worse than about ±300 kHz in most of the remaining countries.

National Meteorological Services need to maintain contact with national radiocommunication authorities in order to keep adequate radiofrequency allocations and to ensure protection from interference for their operations. Radiosonde operations will also need to avoid interference with, or from, data collection platforms (DCP) transmitting to meteorological satellites between 401 and 403 MHz, both downlinks from meteorological satellites between 1 690 and 1 700 MHz and command and data acquisition (CDA) operations for meteorological satellites at a limited number of sites between 1 670 and 1 690 MHz.

12.2 Radiosonde electronics

12.2.1 *General features*

A basic radiosonde design usually comprises three main parts:

(*a*) The sensors plus references;

(*b*) An electronic transducer, converting the output of the sensors and references into electrical signals; and

(*c*) The radio transmitter.

In rawinsonde systems (see Chapter 13), there will also be electronics associated with the reception and retransmission of radionavigation signals, or transponder system electronics for use with secondary radars.

Radiosondes are usually required to measure more than one meteorological variable. Reference signals are used to compensate for instability in the conversion between sensor output and transmitted telemetry. Thus, a method of switching between various sensors and references in a predetermined cycle is required. Most modern radiosondes use electronic switches operating at high speed with typically one measurement cycle lasting between 1 and 2 s. This rate of sampling allows the meteorological variables to be sampled at height intervals of between 5 and 10 m at normal rates of ascent.

12.2.2 *Power supply for radiosondes*

Ideally, radiosonde batteries should be of sufficient capacity to supply the required currents for up to three hours at a temperature of 15°C, without falling more than five per cent below the required output voltages. Also, the output voltages should not decrease by more than 10 per cent for a fall of temperature from 15°C to –10°C. Batteries should be as light as practicable and should have a long storage life. They should also be environmentally safe following use.

However, many modern radiosondes have been developed that can tolerate larger changes in output voltage during flight. Thus, two types of batteries are in common use, the dry-cell type and the water-activated battery.

Dry batteries have the advantage of being widely available at very low cost because of the high volume of production worldwide. However, they have the disadvantages of limited shelf life and of being relatively heavy. The output voltage varies more during discharge than that of the water-activated batteries. Some storage problems have been encountered with lithium batteries in recent years.

Water-activated batteries usually use a cuprous chloride and sulphur mixture. The batteries are lighter than dry cells and can be stored for long periods of time. Their voltage variation during discharge is much less than that of the dry-cell type. The chemical reactions in the water-activated battery generates internal heat, reducing the need for thermal insulation and helping to stabilize the temperature of the radiosonde electronics during flight. These batteries are not manufactured on a large scale for other users. Therefore, they are generally manufactured directly by the radiosonde manufacturers.

12.2.3 *Methods of data transmission*

12.2.3.1 RADIO TRANSMITTER

A wide variety of transmitter designs are in use. Solid-state circuitry is mainly used up to 400 MHz and valve (cavity) oscillators may be used at 1 680 MHz. Some transmitter designs are crystal-controlled to ensure a good frequency stability during the sounding. Good frequency stability during handling on the ground prior to launch and during flight will become more important as radiosonde operations are required to be shared more frequently with other services. At 400 MHz, the most widely used radiosonde type has a transmitter power output of about 250 mW. At 1 680 MHz the most widely used radiosonde type has a power output of about 330 mW. The modulation of the transmitter varies between radiosonde types as indicated in the following sections.

12.2.3.2 VARIABLE AUDIO FREQUENCY TYPE

In this type of radiosonde, the transmitter uses a fixed radio frequency, modulated by an audio frequency signal varying with the output of the radiosonde sensors and references. This audio frequency modulation can be readily controlled by the resistance, capacitance or even inductance of the various radiosonde sensors. In many systems, additional reference inputs are added to the multiplexor cycle, so that the stability of the audio frequency modulation can be checked. In a common radiosonde system that has also been used for Omega NAVAID windfinding, the range of audio frequency used as signal frequencies lies between 7 and 10 kHz. This has the advantage that the modulation from the basic pressure temperature and relative humidity sensors avoids interference with modulation from retransmitted Omega signals (10.2 kHz, 13.6 kHz). Furthermore, the pressure, temperature and humidity (PTU) modulation does not generate harmonics that could corrupt the Omega signals.

The ground system used with a variable audio frequency type of modulation requires a decoding system, dedicated to that specific radiosonde type. The decoder strips out the audio frequency signals. It is able to recognize the cycle of the radiosonde samples and to apply the radiosonde calibration information to compute the meteorological variables. When the audio frequency signals from this type of radiosonde are fed into a speaker, the radiosonde sample cycle produces a recognizable sound signature that can be used to monitor the quality of the radiosonde communication link during flight.

12.2.3.3 CODE-SENDING TYPE

In older radiosonde designs, still in operational use in some national networks, the meteorological sensor outputs are converted into a Morse-code type signal. This is achieved by the movement of contact arms actuated by each sensor across the surface of a rotating segment or disk. The movement of the segment or disc generates the appropriate pulsed code as each arm makes contact.

In many modern radiosonde designs, the meteorological sensor outputs are connected through an oscillator, or an analogue to digital converter, to an onboard microprocessor. This microprocessor converts the sensor outputs into digital code. The digital information is then fed through a modem (frequency shift keying, for example) into the radio transmitter. Control bits can be added to allow monitoring of the integrity of the transmitted data by the receiving equipment. With this type of transmission, the communication link can operate at much lower signal-to-noise levels than with the variable audio frequency type of modulation. Thus, using binary signals (two different modulations from a FSK modem), the bandwidth of the transmitter can be reduced and the radiative power needed to track the radiosonde can be reduced to some extent relative to the audio frequency modulation radiosondes. Radiosonde power consumption is lower and smaller batteries can be used.

The coded data transmitted to the ground system may either be "raw" engineering variables, still needing to be transformed into meteorological values at the ground or, in some cases, actual meteorological variables with the calibration applied directly in the radiosonde by the microprocessor.

Radiosondes transmitting digital codes can also transmit a numeric combination that acts as a radiosonde identifier. This can prevent confusion when several radiosondes are in the air near the ground system and can help the automatic frequency scanning of the radio-receiver when signal fade occurs during the ascent.

Digital radiosondes can also transmit their own sensor calibration data to the ground system. This can eliminate the input by the operator of the calibration coefficients supplied with the radiosonde into the ground processing system prior to the radiosonde ascent.

12.2.3.4 CHRONOMETRIC AND PULSE COUNTING TYPES

In chronometric systems, the meteorological sensors actuate the movement of pointers that make contact with an electrically conducting spiral on an insulated scanning disk or rotating drum. The time (or number of pulses coming from an electrical oscillator) between these contacts and a fixed reference contact is a measure of the pointer deflection and, therefore, of the meteorological sensor output. The pulses generated are then fed into the transmitter circuit.

A modern electronic version of this type of modulation is still used in Switzerland.

12.3 Temperature sensors

12.3.1 *General requirements*

An ideal temperature sensor should have a speed of response to changes of temperature that is fast enough to ensure that systematic bias from thermal lag during an ascent remains less than 0.1 K through any layer of depth of 1 km. At typical radiosonde rates of ascent, this can only be achieved in most locations with a sensor time constant of response faster than 1 s in the early part of the ascent. In addition, the temperature sensors should be designed to be as free as possible from radiation errors introduced by direct or backscattered solar radiation or heat exchange in the infrared. Infrared errors can be avoided by using sensor coatings that have low emissivity in the infrared. In the past, most widely used white sensor coatings had high emissivity in the infrared. Measurements by these sensors were susceptible to significant errors from infrared heat exchange (see section 12.8.3.3).

Temperature sensors also need to be sufficiently robust to withstand buffeting during launch and sufficiently stable to retain accurate calibration over several years. Ideally, the calibration of temperature sensors should be sufficiently reproducible to make individual sensor calibration unnecessary. The main types of temperature sensors in routine use are thermistors (ceramic resistive semiconductors), capacitive sensors, bimetallic sensors and thermocouples, while thin wire sensors have been used for some reference radiosonde sensors.

The rate of response of the sensor is usually measured in terms of the time constant of response, τ. This is defined (as in section 1.6.3) by:

$$dT_e/dt = 1/\tau \cdot (T_e - T) \qquad (12.3)$$

where T_e is the temperature of the sensor and T is the true air temperature.

Thus, the time constant is defined as the time required to respond by 63 per cent to a sudden change of temperature. The time constant of the temperature sensor is proportional to thermal capacity and inversely proportional to the rate of heat transfer by convection from the sensor. Thermal capacity depends on the volume and composition of the sensor, whereas the heat transfer from the sensor depends on the sensor surface area, the heat transfer coefficient, and the rate of the air mass flow over the sensor. The heat transfer coefficient, has a weak dependence on the diameter of the sensor. Thus, the time constants of response of temperature sensors made from a given material are approximately proportional to the ratio of the sensor volume to its surface area. Consequently, thin sensors of large surface area are the most effective for obtaining fast response. The variation of time constant of response with the mass rate of air flow can be expressed as:

$$\tau = \tau_0 \cdot (\rho \cdot v)^{-n} \qquad (12.4)$$

where ρ is the air density, v the air speed over the sensor, and n a constant.

NOTE: for a sensor exposed above the radiosonde body on an outrigger, v would correspond to the rate of ascent, but the air speed over the sensor may be lower than the rate of ascent if the sensor were mounted in an internal duct.

The value of n varies between 0.4 and 0.8 depending on the shape of the variable and on the nature of the air flow (laminar or turbulent). Representative values for the time constant of response of temperature sensors at pressures of 1 000, 100 and 10 hPa, for a rate of ascent at 5 m s^{-1} are shown in Table 12.3. These values are derived from a combination of laboratory testing and comparisons with very fast response sensors during ascent in radiosonde comparison tests.

TABLE 12.3

Typical time constants of response of radiosonde temperature sensors

Temperature sensor	*τ at 1 000 hPa (s)*	*τ at 100 hPa (s)*	*τ at 10 hPa (s)*
Rod thermistor, diameter 1.3 mm	3	8	21
Bead thermocapacitor, diameter 1.2 mm	2.5	6	15
Bimetallic sensor	5–8	12–20	not available
Tungsten wire, diameter 0.013 5 mm	<0.05	<0.05	0.1

12.3.2 *Thermistors*

Thermistors are usually made of a ceramic material whose resistance changes with temperature. The sensors have a high resistance that decreases with absolute temperature. The relationship between resistance, R, and temperature, T, can be expressed approximately as:

$$R = A \cdot exp\,(B/T) \qquad (12.5)$$

where A and B are constants. Sensitivity to temperature changes is very high but the response to temperature changes is far from linear since the sensitivity decreases roughly with the square of the absolute temperature. As the thermistor resistance is very high, typically tens of thousands of ohms, self-heating from the voltage applied to the sensor is negligible. It is possible to manufacture very small thermistors and, thus, fast rates of response can be obtained.

12.3.3 *Thermocapacitors*

Thermocapacitors are usually made of a ceramic material whose permittivity varies with temperature. The ceramic used is usually barium-strontium titanate. This ferro-electric material has a temperature coefficient of permittivity of the order of 10^{-2} per °C. The temperature coefficient is positive at temperatures below the Curie point and negative at temperatures above the Curie point. The most commonly used sensor has a diameter of about 1.2 mm. A new sensor has been designed with a diameter of about 0.1 mm. This measures the change in capacitance between two fine platinum wires separated by a glass ceramic (see Turtiainen, Tammela and Stuns, 1995). This sensor should give improved speed of response and solar heating errors should be much smaller than those of the larger sensor.

12.3.4 *Wire resistors*

This type of sensor has the advantage of high calibration stability and a linear response to temperature changes. Thin wire sensors can have very fast response and radiation errors can be kept small if the absorption of solar radiation by the wire is low. The disadvantage of this type of sensor is that the sensors must be made from very fine wires to provide the moderately high resistance required to interface with the radiosonde transducer. Therefore, the sensors are often rather fragile. Nickel, platinum, and tungsten may be suitable materials. Tungsten wire sensors of 13.5 micron diameter proved generally successful in operational use for about 10 years in one national network. However, sensor fragility was a problem in difficult launch conditions and solar heating in the stratosphere was not very small since the tungsten wires absorbed more solar radiation than ideally desirable.

12.3.5 *Thermocouples*

Copper-constantan thermocouple junctions are also used as a temperature sensor in one national radiosonde (WMO, 1989). Wires of 0.05 mm in diameter are used to form the external thermocouple junction and these provide a sensor with very fast response. The relationship between the thermal electromotive force and the temperature difference between the sensor and its reference is an established physical relationship. The thermocouple reference is mounted internally within the radiosonde in a relatively stable temperature environment. A copper resistor is used to measure this reference temperature. In order to obtain accurate temperatures, stray electromotive force introduced at additional junctions between the sensor and the internal references must also be compensated. As with the wire resistors, this type of sensor is not best suited to very large scale production but may be valuable as an independent reference in future radiosonde comparison tests.

12.3.6 *Bimetallic sensors*

The main bimetallic sensor still in use is a spiral (0.2 mm thick, sensor length uncoiled about 130 mm), mounted on a protective duct at one side of the radiosonde body. The sensor is used on a code-sending radiosonde with a mechanical linkage from the bimetallic spiral to the coding drum. This type of sensor and radiosonde design was widely used in the past in many countries. It has largely been replaced because of the relatively slow time constant of response of the sensor and the large radiation errors that occur, particularly at pressures lower than 20 hPa. Temperature errors from the thermal lag in the bimetallic sensor and its supports are usually too large to ignore (more than 0.3 K), even in the troposphere, and should be compensated to some extent, if possible.

12.3.7 *Exposure*

Radiosonde temperature sensors are best exposed in a position above the main body of the radiosonde (below the body of a dropsonde). Then, air heated or cooled by contact with the radiosonde body or sensor supports cannot subsequently flow over the sensor. This is usually achieved by mounting the sensor on an arm or outrigger that holds the sensor in the required position during flight. For good exposure at low pressures, the supports and electrical connections to the sensor should be thin enough that heating or cooling errors from thermal conduction along the connections should be negligible.

With this method of exposure, the radiosonde temperature sensors are exposed directly to solar radiation and to the infrared environment in the atmosphere. The sensors receive solar radiation during daytime soundings and will exchange long-wave radiation with the ground and the sky at all times. The magnitude of radiation errors is only weakly dependent on the size and shape of the sensors, since convective heat transfer coefficients are only weakly dependent on sensor size. Thus, small radiation errors may be obtained with small sensors, but only when the sensor coating is chosen to provide low absorption for both solar and long-wave radiation. The required coating can be achieved by deposition of a suitable thin metallic layer. Many white paints have high absorption in the infrared and are not an ideal coating for a radiosonde sensor.

An additional consequence of exposing the temperature sensor above the radiosonde body is that when ascending during precipitation or through cloud, the sensor may become coated with water or ice. It is extremely important that the sensor design sheds water and ice efficiently. Firstly, evaporation of water or ice from the sensor when emerging from a cloud into drier layers will cool the sensor below true ambient temperature. Secondly, the absorptivity in the infrared of a temperature sensor that remains coated with ice throughout a flight differs from usual. Thus, an abnormal systematic bias from infrared heat exchange will be introduced into the iced sensor measurements, particularly at low pressures.

Bimetallic sensors and associated supports absorb too much radiation in daylight to be exposed unprotected above the radiosonde. Thus, this type of sensor has to be protected by a radiation shield. The shield should not allow radiation to reach the sensor directly or after multiple reflections. The internal surfaces of the shield should remain at temperatures close to the true atmospheric temperature and should not influence the temperature of the air incident on the sensor. The shielding should not reduce the ventilation of the temperature sensor to any extent and should not trap water or ice when ascending through cloud and precipitation.

While acceptable radiation shield performance may be achieved at high pressures, it becomes increasingly difficult to fulfil all these requirements at low pressure. Good absorption of incoming radiation requires a blackened internal surface on the shield, but this leads to strong coupling of these surfaces to external solar and infrared radiation fields. At low pressures, this results in substantial heating or cooling of the internal surfaces of the shields relative to the ambient atmospheric temperature. Therefore, reliable temperature measurements using radiation shields rapidly become impracticable at the lowest pressures. A compromise shield design might consist of two polished thin aluminium cylinders arranged co-axially with a spacing of 1 or 2 cm.

12.4 **Pressure sensors**

12.4.1 *General aspects*

Radiosonde pressure sensors must sustain accuracy over a very large dynamic range from 3 to 1 000 hPa, with a resolution of 0.1 hPa required at lower pressures. Changes in pressure are usually identified by a small electrical or mechanical change. For instance, the typical maximum deflection of an aneroid capsule is about 5 mm, so that the transducer used with the sensor has to resolve a displacement of about 0.5 μm. Changes in calibration caused by sensor temperature changes during the ascent must also be compensated. These temperature changes may be as large as several tens of degrees, unless the pressure sensor is mounted in a stabilized environment.

Thus, pressure sensors are usually mounted internally within the radiosonde body to minimize the temperature changes that occur. In some cases, the sensor is surrounded by water bags to reduce cooling. When water-activated batteries are used, the heat generated by the chemical reaction in the battery is used to compensate the internal cooling of the radiosonde. However, even in this case, the radiosonde design needs to avoid generating temperature gradients across the sensor and its associated electrical components. If a pressure sensor has an actively controlled temperature environment, the sensor assembly should be mounted in a position on the radiosonde where heat contamination from the pressure sensor assembly cannot interfere with the temperature or relative humidity measurements.

The pressure sensor and its transducer are usually designed so that the sensitivity increases as pressure decreases. The time constant of response of radiosonde pressure sensors is generally very small and errors from sensor lag are not significant.

12.4.2 *Aneroid capsules*

Aneroid capsules have been used as the pressure sensor in the majority of radiosondes. In the older radiosonde designs, the capsules were usually about 50 to 60 mm in diameter. The sensors are made from a metal with an elastic coefficient that is independent of temperature. The measurement of the deflection of the aneroid capsule can be achieved either by an external device requiring a mechanical linkage between the capsule and the radiosonde transducer or by an internal device (see section 12.4.3).

The aneroid sensitivity depends mainly on the effective surface area of the capsule and its elasticity. Capsules can be designed to give a deflection that is linearly proportional to the pressure or to follow some other law, for example close to a logarithmic dependence on pressure. The long-term stability of the capsule calibration is usually improved by seasoning the capsules. This is achieved by exercising the capsules through their full working range over a large number of cycles in pressure and temperature.

When the aneroid is used with a mechanical linkage to a transducer, the sensor usually suffers from a hysteresis effect of about 1 to 2 hPa. This hysteresis must be taken into account during the sensor calibration. The change in pressure during calibration must be of the same sense as that found in actual sounding conditions. The mechanical linkage to the radiosonde transducer often consists of a system amplifying the movement of the capsule to a pointer operating switch contacts or resistive contacts. A successful operation requires that friction be minimized to avoid both discontinuous movements of the pointer and hysteresis in the sensor system.

12.4.3 *Aneroid capsule (capacitive)*

Many modern radiosonde designs use aneroid capsules of smaller diameter (30 mm in diameter or less) with the deflection of the capsule directly measured by an internal capacitor. A parallel plate capacitor used for this purpose is formed by two plates each fixed directly to one side of the capsule. The capacitance, C, is then:

$$C = \epsilon \cdot S/e \qquad (12.6)$$

where S is the surface area of each plate, e is the distance between the plates and ϵ is the dielectric constant. As e is a direct function of the deflection of the capsule, the capacitance C is a direct electrical measurement of the deflection. In many radiosonde sensors, each capacitor plate is fixed to the opposite side of the capsule by mounts passing through holes in the other plate. With this configuration, e decreases when the pressure lowers. The sensitivity of the capacitive sensor is:

$$-\epsilon \cdot S/e^2 \cdot de/dp \qquad (12.7)$$

This will be greatest when e is small and the pressure is smallest. The capacitive sensor described is more complicated to manufacture but is best suited for upper air measurements, as the sensitivity can be 10 times greater at 10 hPa than at 1 000 hPa. The value of the capacitance is usually close to 6 pF.

Capacitive aneroid capsules are usually connected to a resistance-capacitance (RC) electronic oscillator with associated reference capacitors. This arrangement needs to measure very small variations of capacity (for example 0.1 per cent change in a maximum of 6 pF) without any significant perturbation of the oscillator from changes in temperature, power supply or ageing. Such high stability in an oscillator is difficult to achieve at a low price. However, one solution is to multiplex the input to the oscillator between the pressure sensor and two reference capacitors. A reference capacitor C_1 is connected alone to the oscillator, then in parallel with C_p, the pressure sensor capacitor, and then in parallel with a second reference C_2 to provide a full-scale reference.

The calibration of an aneroid capacitive sensor will usually have significant temperature dependence. This can be compensated either by referencing to an external capacitor having a temperature coefficient of similar magnitude or during data processing in the ground system using calibration coefficients from factory calibrations. The correction applied during processing will depend on the internal temperature measured close to the pressure sensor. In practice, both of these compensation techniques may be necessary to achieve the required accuracy.

12.4.4 *Silicon sensors*

Following rapid developments in the use of silicon, reliable pressure sensors can now be made with this material. A small cavity is formed from a hole in a thick semiconductor layer. This hole is covered with a very thin layer of silicon, with the cavity held at a very low pressure. The cavity will then perform as a pressure sensor, with atmospheric pressure sensed from the deflection of the thin cover of silicon.

The deflection of the thin layer can be measured using a piezoresistive sensor. In this case, strain gauges are diffused onto the surface of the cavity cover. The electrical resistance of the strain gauges changes with the deflection of the thin silicon layer. The gauges are coupled as a Wheatstone Bridge to provide a linear variation of resistance with pressure. This type of sensor is commonly used in industry. Sensor output has a linear dependence on pressure and calibration remains stable with time. However, the strain gauges have a strong temperature dependence. Without temperature compensation, a change in temperature of 1 K will produce a 2 hPa pressure error. This strong temperature dependence may be reduced by referencing the sensor output to a semiconductor resistance with a similar temperature dependence as the strain gauge. However, if a referencing resistance is used, the linearity of the sensing system is lost and the dependence on temperature becomes complex. Thus, it is preferable to operate the sensor in a temperature-stabilized environment. This has already been achieved in one operational radiosonde design. Otherwise, it would be necessary to make individual sensor calibrations of pressure against temperature over the temperature range usually experienced by the pressure sensor during flight. The pressure sensor measurements would then have to be corrected for changes in sensor temperature during data processing by the ground system.

A second method of detecting the deflection of the silicon is to use a capacitive sensor. In this case, the thin silicon layer across the cavity is coated with a thin metallic layer, and a second metallic layer is used as a reference plate. The deflection of the silicon cover is measured by using the variation in the capacitance between these two layers. This type of sensor has a much lower temperature dependence than the strain gauge sensor; it has been implemented in a new operational radiosonde design. The very small sensor size should avoid the calibration errors in the larger capacitive aneroid sensors introduced by changes in temperature gradients across the aneroid sensor and associated electronics during an ascent.

12.4.5 *Hypsometers*

Hypsometer sensors derive pressure from a measurement of the boiling temperature of a liquid. One operational radiosonde uses a water hypsometer. The temperature sensor is attached to an indentation in the bulb of a glass flask containing the water. This bulb is about 15 mm in diameter and about 20 mm in depth. The stem of the flask is open to the atmosphere and is about 160 mm in length and about 8 mm in diameter. The water is heated internally during flight to ensure that boiling is sustained. The sensitivity of the water hypsometer over the range of pressures found during a flight is shown in Table 12.4. At high pressures, shortly

TABLE 12.4

The sensitivity of a water hypsometer at selected atmospheric pressures

Pressure (hPa)	*Boiling temperature (°C)*	*Change in boiling point for a given pressure change (°C/hPa)*
1 000	100	≈0.03
100	46	≈0.2
10	7.2	≈1.5

after launch, the boiling temperature must be measured with a random error of 0.01 K in order to provide a pressure measurement with random error similar to the best aneroid capacitive sensors. Random errors within a factor of two of this have been achieved with the operational systems, but it is difficult to keep the absolute errors in temperature (and hence pressure) as small. On the other hand, operational hypsometer sensors provide much better accuracy than aneroid capsules at very low pressures, with random and systematic errors in hypsometer measurements being less than 0.1 hPa at 10 hPa (see Richner, Joss and Ruppert, 1996).

The successful operation of a hypsometer requires that the liquid neither superheats nor ceases to boil during the ascent.

12.4.6 *Use of radar height observations instead of pressure sensor observations*

12.4.6.1 GENERAL

When a radar is in use for windfinding, radar height measurements may provide an alternative to the use of a radiosonde pressure sensor. The calculation of the pressure at a given time into flight can be derived from radar height and surface pressure combined with the radiosonde observations of temperature and humidity up to the given time. The elimination of the pressure sensor would provide a considerable saving in the cost of the radiosondes. In practice, most operational windfinding radars have difficulty in measuring height with sufficient accuracy to satisfy user requirements for pressure and height measurements in the troposphere. On the other hand, radar heights may provide effective checks on pressure sensor performance when pressures are very low.

When radiosonde preparation procedures are standardized throughout a network, radiosonde pressure errors will mainly depend on the accuracy of the manufacturer's calibration and the subsequent sensor stability. Thus, pressure errors will usually be similar at all radiosonde stations in the network that use radiosondes from a given calibration facility. In contrast, the errors in radar height data depend upon the installation and calibration of each individual radar at each station. Thus, it is much more difficult to obtain consistency from station to station in geopotential height and pressure measurements if a network depends entirely on radar height measurements.

12.4.6.2 METHOD OF CALCULATION

The algorithms for computing geometric height from windfinding radar observations of slant range and elevation and for the conversion of geometric heights to geopotential heights are included in WMO (1986). The actual algorithm used with secondary radar systems in Russia can be found in WMO (1991). If radar height observations are used as a replacement for pressure sensor observations, the heights need to be corrected for the effects of the Earth's curvature and radio-wave refraction before pressure is computed. Corrections for refraction can be made using seasonal averages of atmospheric profiles, but optimum pressure accuracy might require height corrections for the conditions found in individual flights.

12.4.6.3 SOURCES OF RADAR HEIGHT ERRORS

The effect of radar observational errors upon windfinding is considered in Chapter 13. However, for radar heights, errors in elevation (random and systematic) are much more significant than for winds. Systematic bias in slant range is also more critical for height than for wind measurements. Therefore, radars providing satisfactory wind measurements often have errors in elevation and slant range that prevent best quality height (and hence pressure) measurements.

Small but significant systematic errors in elevation may arise from a variety of sources:

(*a*) Misalignment of the axes of rotation of azimuth and elevation of the radar during manufacture. If this is to be avoided, the procurement specification must clearly specify the accuracy required;

(*b*) Errors in levelling the radar during installation and in establishing the zero elevation datum in the horizontal;

(*c*) Differences between the electrical and mechanical axes of the tracking aerials, possibly introduced when electrical components of the radar are repaired or replaced.

Errors may arise from errors introduced by the transducer system measuring the radar elevation angle from the mechanical position of the tracking aerial.

Systematic errors in slant range may arise from:

(*a*) A delay in triggering the range-timing circuit or incorrect compensation for signal delay in the radar detection electronics;

(*b*) Error in the frequency of the range calibrator.

Thus, radiosonde systems operating without pressure sensors and relying solely on radar height measurements require frequent checks and adjustments of the radars, as part of the routine station maintenance. These systems are not suitable for use in countries where technical support facilities are limited.

12.5 Relative humidity sensors

12.5.1 *General aspects*

The successful operation of a radiosonde relative humidity sensor relies on a rapid exchange of water molecules between the sensor and the atmosphere. If a relative humidity sensor is to provide reliable measurements throughout the troposphere it must be able to resolve to 1 per cent of saturated water vapour pressures from 46 hPa at 30°C down to at least 0.06 hPa at –50°C. At temperatures below 0°C, relative humidity sensors should be calibrated to report relative humidity with respect to a water surface.

In dry conditions (no cloud, fog or precipitation) most modern relative humidity sensors agree fairly closely at temperatures higher than about –10°C and show a similar relative humidity structure in the vertical. However, satisfactory relative humidity sensor operation is often extremely difficult to obtain at low temperatures and pressures. If the free exchange of water molecules between the sensor and the atmosphere is hampered once the temperature falls during an ascent, then contamination of the sensor from high water vapour concentrations earlier in the ascent may cause substantial systematic bias in sensor measurements at the lowest temperatures.

The time constant of response of a relative humidity sensor increases much more rapidly during a radiosonde ascent than the time constant of response of the temperature sensor. Table 12.5 provides approximate values of time constant of response for the three main sensor types. These values represent the time constant of response for changes between about 70 and 30 per cent relative humidity. The time constants of response of the goldbeater's skin sensors for a given temperature are much larger when exposed to very high or very low relative humidity.

Carbon hygristor sensors are usually mounted in a protective duct in the radiosonde and thin-film sensors are usually mounted on an outrigger from the radiosonde and protected with a cover against precipitation. However, recent radiosonde comparison tests did not identify any significant difference in the time constants of response of the most widely used carbon hygristor and thin-film capacitor sensors at temperatures higher than –30°C.

However, the thin-film capacitors usually have much shorter time constants of response than the carbon hygristors at temperatures lower than –40°C. In particular, the response speeds of carbon hygristor sensors to decreases in relative humidity at temperatures of –50°C become almost as slow as those of the goldbeater's skin sensors (at least 10 minutes). In contrast, the carbon hygristor response at similar temperatures to increases in relative humidity with time is clearly faster than that of the goldbeater's skin sensor. The thin-film capacitors will usually have a time constant of response of about one or two minutes in either of these conditions. The hygristor performance at very low temperatures does not appear to be related to the design of the protective duct for the hygristor. Thus, when atmospheric water vapour concentrations fall with time at very low temperatures, the diffusion of water vapour molecules out of the carbon hygristor seems to be very slow. On the other hand, water molecules are able to diffuse into the sensor at a faster rate if atmospheric water vapour concentrations rise with time at a similar temperature.

The calibration of most relative humidity sensors is temperature dependent. The correction for this dependence must be applied during data processing by the ground system, if the accuracy claimed for the sensor at room temperatures in the laboratory is to be obtained throughout most of the troposphere.

Most relative humidity sensors require protection from contamination by precipitation early in the ascent. The evaporation of contamination from protective covers, internal duct surfaces or sensor supports early in flight may also cause errors in the reported relative humidity.

None of the operational radiosonde relative humidity sensors are reliable enough for good quality relative humidity measurements at low temperatures and low pressures in the stratosphere.

12.5.2 *Thin-film capacitors*

Capacitive thin-film sensors are now used by several operational radiosonde designs. The first widely used sensor relied on the variation of the dielectric constant of a polymer film with ambient water vapour pressure. The lower electrode of the capacitor was formed by etching a metal-coated glass plate (typically 4 mm square and 0.2 mm thick) and then coating this with an active polymer approximately one micron thick. The upper electrode was vacuum-evaporated onto the polymer surface and was permeable to water vapour. Sensor capacitance was a nearly linear function of relative humidity; temperature dependence of calibration was small. Subsequent laboratory investigations of the sensor performance showed that hysteresis was relatively small (less than three per cent relative humidity) as long as the sensor was not contaminated by precipitation on the electrodes. After several years of operational use, a thin coating was added to the upper electrode to improve stability of performance in wet ascents. A newer sensor uses a different polymer that is more stable when used in wet conditions. This sensor requires a higher order polynomial calibration than the earlier design, but this can now be accommodated by operational systems. Data processing in most radiosonde ground systems is now fully automated and capable of dealing with this level of complexity. Although this sensor is more stable in wet conditions, it still suffers from contamination after passing through thick cloud at low levels. It has been

TABLE 12.5

Time constant of response of relative humidity sensor, τ (in seconds) for a range of temperatures

Sensor	*τ at 20°C*	*τ at 10°C*	*τ at 0°C*	*τ at –10°C*	*τ at –20°C*	*τ at –30°C*
Goldbeater's skin	6	10	20	50	100	200
Carbon hygristor	0.3	0.7	1.5	4	9	20
Thin-film capacitor	0.3	0.7	1.5	4	9	20

suggested that this contamination should be eliminated by heating the relative humidity sensor periodically during flight (Paukkunen, 1995). Optimum performance from thin-film sensors requires careful calibration of sensor performance in the factory over the whole range of temperatures encountered in the troposphere where measurements will be reported.

12.5.3 *Carbon hygristors*

Carbon hygristor sensors are made by suspending finely divided carbon particles in a hygroscopic film. A modern version of the sensor consists of a polystyrene strip (thickness about 1 mm, length about 60 mm and width about 18 mm) coated with a thin hygroscopic film containing carbon particles. Electrodes are coated along each side of the sensor. Changes in the ambient relative humidity lead to dimensional changes in the hygroscopic film such that the resistance increases progressively with humidity. The resistance at 90 per cent relative humidity is about 100 times as large as the resistance at 30 per cent relative humidity. Corrections can be applied for temperature dependence during data processing. The sensors are usually mounted on a duct within the radiosonde body to minimize the influence of precipitation wash and to prevent direct solar heating of the sensor.

The successful implementation of this sensor type requires a manufacturing process that is well controlled so that the temperature dependence of the sensors does not have to be determined individually. The hygristors will normally be subjected to many seasoning cycles over a range of relative humidity at room temperatures in the factory to reduce subsequent hysteresis in the sensor during the radiosonde ascent. The resistance of the sensor can be adjusted to a standard value during manufacture by scratching a part of the carbon film. In this case, the variables can be issued with the appropriate standard resistance value for the specified conditions, and the sensors can be made interchangeable between radiosondes without further calibration. The sensor must be kept sealed until just before it is used, and the hygroscopic surface must not be handled during insertion into the sensor mount on the radiosonde.

12.5.4 *Goldbeater's skin sensors*

Goldbeater's skin (beef peritoneum) is still used in some networks where thin-film capacitors or carbon hygristors have yet to be introduced. The length of a piece of goldbeater's skin changes by between 5 to 7 per cent for a change in humidity from 0 to 100 per cent. While useful measurements can be obtained at temperatures higher than -20°C, sensor response becomes extremely slow at temperatures lower than this (see Table 12.5). Goldbeater's skin sensors also suffer from significant hysteresis following exposure to low humidities.

The goldbeater's skin used for humidity variables should be single-ply and unvarnished, with a thickness of about 0.03 mm. The skin should be mounted with a tension of about 20 g cm^{-1} width and should be seasoned for several hours, in a saturated atmosphere, while subjected to this tension. To minimize hysteresis, it is advisable to condition the variable by keeping it in a saturated atmosphere for 20 minutes both before calibration and before use. Calibration should be made during a relative humidity cycle from damp to dry conditions. The variable must be protected from rain during flight.

The time constant of response of the sensor is much higher than the values quoted in Table 12.5 at very high and very low humidities (McIlveen and Ludlam, 1969). Thus, it is difficult to avoid bias in goldbeater's skin measurements during an ascent (low bias at high humidity, high bias at low humidity) even in the lower troposphere.

12.5.5 *Lithium chloride sensors*

One national network still uses lithium chloride sensors. These are a resistive type of sensor, where a polystyrene sensor strip is coated with an electrolytic film of lithium chloride dissolved in polyvinyl acetate. Electrodes are coated along the two long edges of the sensor in a similar manner to the carbon hygristor sensor. The resistance of the lithium chloride sensor decreases as relative humidity increases, from about 10 MΩ to 5 kΩ for a change of humidity from 15 to 100 per cent at room temperature. The calibration of lithium chloride sensors is strongly dependent on temperature. The sensors are not stable when exposed to high relative humidity for many hours and must be stored in dry conditions. As with goldbeater's skin, the time constants of sensor response at very high and very low humidity are very slow. In Phase II of the WMO Radiosonde Comparison this sensor did not provide reliable measurements at pressures lower than 600 hPa (WMO, 1987).

12.5.6 *Exposure*

Rapid changes in the relative humidity of large amplitude (greater than 25 per cent), particularly above and below cloud layers or above fog, are common during radiosonde ascents. Accurate measurements of these changes are significant for users. However, accurate measurements require that the humidity sensor is well ventilated, but the sensor also needs to be protected, as far as possible, from deposition of water or ice onto the surface of the sensor or its supports and also from solar heating.

Thus, the smaller relative humidity sensors, such as thin-film capacitors, may be covered by a small protective cap and mounted on an external outrigger. The larger sensors are usually mounted on an internal duct or a large protective duct on the top or side of the radiosonde body. The duct design should be checked to ensure that air flow into the duct is sufficient to ensure adequate sensor ventilation during the ascent. The duct should also be designed to shed ice or water, encountered in cloud or heavy precipitation, as quickly as possible. The duct should protect the sensor from incident solar radiation and should not allow significant backscattering of solar radiation onto the sensor.

Protective covers or duct coatings should not be hygroscopic.

12.6 Ground station equipment

12.6.1 *General features*

The detailed design of the ground equipment of a radiosonde station will depend on the type of radiosonde that is used. However, the ground station will always include:

(*a*) An aerial plus radio receiver for receiving the signals from the radiosonde;
(*b*) Equipment to decode the modulation of the radiosonde signals and to convert the signals to meteorological units; and
(*c*) Equipment to present the meteorological measurements to the operator so that the necessary messages can be transmitted to the users, as required.

Other equipment may be added to provide wind measurements when required (for example, radar interface, Loran C, Omega or GPS trackers).

The output of the decoder should usually be input to a computer for archiving and subsequent data processing and correction. However, in older systems, the decoded signals may be either recorded on a strip-chart or connected to a printer. These older types of systems should be replaced as soon as possible, since modern computers can archive and process the radiosonde signals much more reliably than an operator using manual methods.

Modern ground station systems can be either purchased as an integrated system from a given manufacturer, or may be built up from individual modules supplied from a variety of sources. The integrated system may be lighter and more compact, but may often only be used with one specific radiosonde type. If maintenance support will mainly be provided by the manufacturer or its agents, and not by the operators, then an integrated system may be the preferred choice. A system comprised of individual modules may be readily adapted to different types of radiosonde. This could be achieved by adding relevant decoders, without the extra cost of purchasing the remainder of the integrated ground system offered by each manufacturer. A modular type of system may be the preferred option for operators with their own technical and software support capability, independent of a given radiosonde manufacturer.

NOTE: The rate of development in modern electronics is such that it will prove difficult for manufacturers to provide in-depth support to particular integrated systems for longer than 10 to 15 years. Thus, replacement cycles for integrated ground systems should be taken as about 10 years, when planning long-term expenditure.

12.6.2 *Software for data processing*

Satisfactory software for a radiosonde ground system is much more complicated than that needed merely to evaluate, for example, standard level geopotential heights from accurate data. Poor quality measurements need to be rejected and interpolation procedures developed to cope with small amounts of missing data. There is a serious risk that a programmer not thoroughly versed in radiosonde work will make apparently valid simplifications that introduce very significant errors under some circumstances. For instance, if reception from the radiosonde is poor, it is dangerous to allow too much interpolation of data using mathematical techniques that will become unstable when data quality is generally poor, but will be quite stable when data quality is generally good. Furthermore, certain problems with signal reception and pressure errors near launch are often compensated by adjusting the time associated with incoming data. This may not cause significant errors to reported measurements, but can make it almost impossible to check radiosonde sensor performance in radiosonde comparison tests.

Thus, it is essential to use the services of a radiosonde specialist or consultant to provide overall control of the software design. The specialist skills of a professional programmer will usually be necessary to provide efficient software. This software will include the display and interactive facilities for the operator that are required for operational use. The software must be robust and not easily crashed by inexpert operators. In the last decade, most software for commercial radiosonde ground systems has required at least two or three years of development in collaboration with testing by national Meteorological Services. This testing had to be performed by using highly skilled operators and test staff, until the software had become thoroughly reliable in operation. The ground system software then became suitable for use by operators without any significant specialized computing skills.

The software in the ground system should be well documented, including clear descriptions of the algorithms in use. The overall system should be designed to allow sounding simulations for testing and comparison purposes. It is proposed that sets of known raw pressure, temperature and humidity data records should be used to check the reliability of newly developed software. Software errors are often the limiting factors in the accuracy of data reports from the better radiosonde types.

12.7 Radiosonde operations

12.7.1 *Control corrections immediately before use*

It is recommended that radiosonde measurement accuracy should always be checked in a controlled environment before the radiosonde is launched. These control checks should be made with the radiosonde ready for flight and should take place a few minutes before release. The aim is to prevent the launch of faulty radiosondes. A further aim may be to improve calibration accuracy by adjusting for small changes in calibration that may have occurred when the radiosonde was transported to the launch site and during storage.

These control checks are usually performed indoors. They can be made in a ventilated chamber with reference temperature and relative humidity sensors of suitable accuracy to meet user specifications. Relative humidity can then be checked at ambient humidity and lower and higher humidities, if necessary. If no reference psychrometer is available, then known humidity levels can be generated by saturated saline solutions or silica gel.

The differences between the radiosonde measurements and the control readings can be used to adjust the calibration curves of the sensors prior to flight. The sensors used for controlling the radiosonde must be regularly checked in order to avoid long-term drifts in calibration errors. A suitable software adjustment of radiosonde calibration normally improves the reproducibility of the radiosonde measurements in flight to some extent. The type of adjustment required will depend on the reasons for calibration shift following the initial calibration during manufacture and will vary with radiosonde type.

If large discrepancies relative to the control measurements are found, then the radiosonde may have to be rejected as falling outside of the manufacturer's specification and returned for replacement. Maximum tolerable differences in ground checks need to be agreed upon with the manufacturer when purchasing the radiosondes.

It is also wise to monitor the performance of the radiosonde, when it is taken to the launch area. The reports from the radiosonde should be checked for compatibility with the surface observations at the station immediately before launch.

In view of the importance of this stage of the radiosonde operation, the Commission for Instruments and Methods of Observation[2] recommends that:

(*a*) The performance of the radiosonde pressure, temperature, and relative humidity sensors should be checked in a controlled environment, such as a calibration cabinet or baseline check facility prior to launch;

(*b*) The baseline check should be automated as far as possible to eliminate the possibility of operator error;

(*c*) The temperature and relative humidity observations should also be checked against the standard surface temperature and relative humidity observations at the station immediately before the launch.

12.7.2 *Methods of deployment*

Radiosondes are usually carried by balloons rising with a rate of ascent of between 5 and 8 m s^{-1}, depending on the specification and characteristics of the balloon in use (see Chapter 10, Part II). These rates of ascent allow the measurements to be completed in a timely fashion — i.e. about 40 minutes to reach 16 km and about 90 minute to reach heights above 30 km — so that the information can be relayed quickly to the forecast centres. The designs and positioning of the temperature and relative humidity sensors on the radiosonde are usually intended to provide adequate ventilation at an ascent rate of about 6 m s^{-1}. Corrections applied to temperature for solar heating errors will usually only be valid for the specified rates of ascent.

A radiosonde transmits information to a ground station that is usually at a fixed location. However, advances in modern technology mean that fully automated radiosonde ground systems are now very small. Therefore, the ground systems are easily deployed as mobile systems on ships or in small vans (or trailers) on land.

Dropsondes deployed from research aircraft use parachutes to slow the rate of descent. Temperature sensors are mounted at the bottom of the dropsonde. Rates of descent are often about 12 m s^{-1} to allow the dropsonde measurement to be completed in about a quarter of an hour. The high descent rate allows one aircraft to deploy sufficient dropsondes at a suitable spacing in the horizontal for mesoscale research (less than 50 km). The dropsonde transmissions will be received and processed on the aircraft. Systems under development will be able to take, transmit direct readings, and operate automatically under program control. Also, systems are also under development to use remotely piloted vehicles to deploy dropsondes.

12.7.3 *Radiosonde launch procedures*

Once a radiosonde is prepared for launch, the meteorological measurements should be checked against surface measurements either in an internal calibration chamber or externally against surface observations in a ventilated screen. This is necessary since the radiosonde may have been damaged during shipment from the factory, manufacture may have been faulty, or sensor calibrations may have drifted during storage. Radiosondes producing measurements with errors larger than the limits specified in the procurement contract should be returned to the manufacturer for replacement.

Radiosondes are usually launched by hand or by using a launch aid from a shed or shelter. The complexity of the shed and the launch procedures will depend on the gas used to fill the balloon (see Chapter 10, Part II) and on the strength and direction of the surface winds at the site. Launching in strong winds is aided by the use of unwinders that allow the suspension cord for the radiosonde to deploy slowly following the launch. Very strong surface winds require unwinders that deploy the suspension cord at rates as low as 0.5 to 1 m s^{-1}.

Automatic launch systems for radiosondes are commercially available. These may offer cost advantages at radiosonde stations where staff are solely used

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[2] Recommended by the Commission for Instruments and Methods of Observation at its eleventh session, 1993, through Recommendation 9 (CIMO-XI).

for radiosonde operations. The systems may not be suitable for operations in very exposed conditions where very strong surface winds are common.

If users require accurate vertical structure in the atmospheric boundary layer, the surface observations incorporated in the upper air report should be obtained from a location close to the radiosonde launch site. The launch site should also be representative of the boundary layer conditions relevant to the surface synoptic network in the area. It is preferable that the operator (or automated system) should make the surface observation immediately after the balloon release rather than prior to the balloon release. The operator should be aware of inserting surface observations into the ground system prior to launch, as meteorological conditions may change before launch actually takes place when a significant delay in the launch procedure happens (for instance, a balloon burst prior to launch, or air traffic control delay).

As the radiosonde sensors will only function reliably when correctly ventilated, radiosondes need to be well ventilated prior to launch if the correct vertical structure in the atmospheric boundary layer is to be measured. When it is raining it will be necessary to provide some protection to the radiosonde sensors prior to launch. In this case, a ventilated screen may be useful in helping to condition the radiosonde for launch.

12.7.4 *Radiosonde suspension during flight*

The radiosonde must not be suspended too close to the balloon in flight. This is because the balloon is a source of contamination for the temperature and relative humidity measurements. A wake of air, heated from contact with the balloon surface during the day, and cooled to some extent during night, is left behind the balloon as it ascends. The balloon wake may also be contaminated with water vapour from the balloon surface after ascent through clouds. The length of suspension needed to prevent the radiosonde measurements suffering significant contamination from the balloon wake varies with the maximum height of observation. This is because the balloon wake is heated or cooled more strongly at the lowest pressures. A suspension length of 20 m may be sufficient to prevent significant error for balloons ascending only to 20 km. However, for balloons ascending to 30 km or higher, a suspension length of about 40 m is more appropriate (see for instance WMO, 1994*b*).

NOTE: When investigating the influence of the balloon wake on radiosonde measurements it is vital to ensure that the sensors on the radiosonde used for the investigation are correctly exposed. The sensors must be mounted so that it is impossible for air that has had contact with other surfaces on the radiosonde to flow over the radiosonde sensor during ascent. Possible sources of heat or water vapour contamination from the radiosondes are the internal surfaces of protective ducts, the mounts used for the sensor, or the external surfaces of the radiosonde body.

12.7.5 *Public safety*

The radiosonde design must fall well within existing air traffic safety regulations as to size, weight and density. These should ensure that the radiosonde should not cause significant damage if it collides with an aircraft or if it is ingested by the aircraft engine. In many countries, the National Air Traffic Authority issues regulations governing the use of free flight balloons. Balloon launch sites must often be registered officially with the air traffic control authorities. Balloon launches may be forbidden or only possible with specific authorization from the air traffic controllers in certain locations. The situation with respect to flight authorization must be checked before new balloon launch locations are established.

In some countries, safety regulations require that a parachute or other means of reducing the rate of descent after a balloon burst must also be attached to the radiosonde suspension. This is to protect the general public from damage. The parachute needs to reduce the rate of descent near the surface to less than about 6 m s^{-1}. The remains of the balloon following burst usually limit the rate of descent at lower levels. However, on occasion, most of the balloon will be detached from the flight rig following burst and the rates of descent will be too high unless a parachute is used.

It is important that radiosondes should be environmentally safe after returning to Earth or after falling in the sea, whether picked up by the public or by an animal, or left to decay.

12.8 Errors of radiosondes

12.8.1 *General considerations*

12.8.1.1 TYPES OF ERROR AND POSSIBLE REFERENCES

This section contains a detailed discussion of the errors of radiosonde sensors. The consequential errors in calculated geopotential heights were discussed in section 12.1.3.7.

Errors in measurement by radiosondes may be classified into three types (WMO, 1975):

(*a*) Systematic errors characteristic of the type of radiosonde in general;

(*b*) Sonde error, representing the variation in errors that persist through thick layers in the vertical for a particular type of radiosonde from one flight to the next;

(*c*) Random errors in individual observations, producing the scatter superimposed on the sonde error through a given ascent.

At present, it is still difficult to compare radiosonde data with absolute references. However, high precision tracking radar measurements do allow systematic errors in geopotential height measurements to be quantified in special tests. These results can then be used to identify systematic errors in radiosonde pressure sensor measurements, given that errors in temperature measurements are known to be relatively small.

Most of the better modern radiosondes measure temperatures at night that fall within a range of ± 0.3 K

(WMO, 1994*a*). Thus at night, it is possible to identify systematic errors that bias radiosonde measurements away from this consensus. Daytime temperature comparisons with the same certainty are still not feasible. However, the development of the NASA-ATM three-thermistor technique offers a way forward for daytime measurements (Schmidlin, Sang Lee and Ranganayakama, 1995).

Relative humidity measurements can be checked at high humidities when the radiosondes pass through clouds at temperatures higher than 0°C. The vertical structure in relative humidity reported by radiosondes, including the presence of very dry layers, can be validated by comparing with Raman lidar measurements.

In most radiosonde comparison tests, the results from one radiosonde design are compared with those of another to provide an estimate of their systematic differences. The values of sonde error and of the random errors can usually be estimated from the appropriate method of computing the standard deviations of the differences between the two radiosonde types. The most extensive series of comparison tests performed since 1984 have been those of the WMO International Radiosonde Comparison (WMO, 1987; 1991; 1996*b*). The results from these and other tests to the same standards in the United Kingdom, United States and Switzerland will be quoted in the subsequent sections.

12.8.1.2 SOURCES OF ERROR OTHER THAN SENSOR DESIGN, CALIBRATION AND EXPOSURE

It is extremely important to perform pre-flight radiosonde checks very carefully, since mistakes in measuring values for control data used to adjust calibrations can produce significant errors in measurement during the ascent. Observation errors in the surface data obtained from a standard screen and then included in the radiosonde message must also be avoided. An error in surface pressure will affect all the computed geopotential heights. For the same reason, it is important that the surface pressure observation should correspond to the official station height.

Random errors in modern radiosonde measurements are now generally small. This is the result of improved radiosonde electronics and multiplexing, more reliable data telemetry links between the ground station, and reliable automated data processing in the ground station. Thus, the random errors are usually less significant than systematic radiosonde errors and flight-to-flight variation in sensor performance and calibration (sonde error). However, random errors may become large if there is a partial radiosonde failure in flight, if interference is caused by another radiosonde using a similar transmission frequency, or if the radiosondes are at long slant ranges and low elevations that are incompatible with the specification of the ground system receiver and aerials.

Thus, errors in radiosonde measurements may be caused not only by the radiosonde sensor design and problems with calibration in the factory during manufacture, but also by problems in the reception of the radiosonde signal at the ground and the effect on subsequent data processing. When signal reception is poor, data-processing software will often interpolate values between the occasional measurements judged to be valid. Under this circumstance, it is vital that the operator is aware of the amount of data interpolation that is occurring. Data quality may be so poor that the flight should be terminated and a replacement radiosonde launched.

Software errors in automated systems often occur in special circumstances that are difficult to identify without extensive testing. Usually, the errors result from an inadvertent omission of a routine necessary to deal with a special situation or combination of events normally dealt with instinctively by an expert human operator.

12.8.2 *Pressure errors*

The systematic errors and the radiosonde error (flight-to-flight variation at 2 standard deviations) have been estimated from the WMO Radiosonde Comparison for selected radiosonde types and from associated tests where radars have been used to check pressure sensor performance. The results are shown in Table 12.6. The range of values in systematic error usually represents the spread of results from several tests. However, in those cases when a test was performed without a radar to cross-check the pressure sensor performance, this may be an indication of uncertainty in the error estimate.

Aneroid capsules are liable to change calibration unless they have been well seasoned through many pressure cycles over their working range before use. Software corrections applied during data processing, but based on ground-control readings before launch go some way toward reducing these errors. Nevertheless, corrections based on ground checks rely on a fixed error correction pattern across the working range. In practice, the change in pressure sensor calibration may be more variable over the working range. This was found to be the case in one widely used system where the software corrections only eliminate about half the variation found in the ground control checks before flight.

Hysteresis errors during ascent should be largely eliminated by calibration but they become important if observations during descent are used, in which case appropriate corrections should be applied. Errors due to backlash in mechanical linkages should be reduced as far as possible. Systematic errors will arise in the application of temperature corrections if the pressure unit is not at the assumed temperature.

Basic aneroid systems represented in Table 12.6 are the UK RS3 (inductive transducer), VIZ 1392 (baroswitch), Philips RS4 (baroswitch), Meisei RS2-80 (baroswitch) and China SMG (mechanical linkage to code sending radiosonde). The Meisei radiosondes in Japan had the most comprehensive pre-flight ground

TABLE 12.6

Estimates of the systematic error and radiosonde error (flight-to-flight) in pressure of selected radiosonde systems from the WMO International Radiosonde Comparison and associated tests

Radiosonde type	*System error at 850 hPa (hPa)*	*System error at 100 hPa (hPa)*	*System error at 10 hPa (hPa)*	*Sonde error at 850 hPa (hPa)*	*Sonde error at 100 hPa (hPa)*	*Sonde error at 10 hPa (hPa)*
Vaisala RS80	1.0 to 0.5	–1 to –0.5	–0.5 to 0	1	0.6	0.4
VIZ MkII	0 to 1	0.7 to 1.1	0.3 to 0.7	1	0.6	0.4
Meisei RS2-91	0.2 to 1	–0.1 to 0.5	–0.2 to 0.2	1	0.6	0.6
AIR Intellisonde	0.2 to 1	0.3 to 1.3	–0.2 to 1.2	1	0.6	0.4
UK RS3	–0.6 to 0	–0.7 to –0.2	–1 to –0.1	1.4	1.6	2
VIZ 1392	–0.1 to 0.5	–0.5 to 0.1	–0.5 to –0.2	3.6	1.6	1
Philips RS4	2.2	3.2	2.2	3.6	2.8	2
Meisei RS2-80	–0.5 to 0.3	0 to 0.6	–0.2 to 0.2	2	0.8	0.4
China SMG	–3.3 to –1.8	–2.5 to –0.8	–1.3 to 0.5	5	3	2.6
Russia MRZ	–1.5 to –0.5	–1.2 to –0.8	0 to 0.2	7	3.5	0.5
Switzerland SRS-400	1 to 1.5	0.5 to 0.7	0.1 to 0.2	1.6	1	0.2

checks and this appears to have led to smaller systematic errors. Systematic biases for all aneroid sensors were not always small for a variety of reasons, including poor factory calibrations, difficulties in ground checking certain types of radiosonde, and inadequate temperature compensation during the ascent. Sonde errors for pressure were generally in the range of 1 to 4 hPa. Evidence from comparisons with radar heights suggests that earlier radiosondes of similar sensor type had larger errors than those shown here.

The Vaisala RS80, VIZ MkII, AIR Intellisonde and Meisei RS2-91 radiosondes all have capacitive aneroid sensors, but of differing design. The sonde errors for the capacitive aneroids are significantly smaller than for the other aneroid types, with values usually lower than 1 hPa at all pressures. However, capacitive aneroid capsules have significant systematic errors, particularly when the internal temperature of the radiosonde changes and temperature gradients develop across the sensor and its associated electronics. The resultant systematic error may be larger than the flight-to-flight variation in sensor performance. Systematic error with capacitive aneroids is usually not larger than ±1.5 hPa at high pressures and ±1.0 hPa at very low pressures. However, errors may be larger if the pressure sensors experience very large thermal shock on launch. This might occur in polar conditions if the radiosonde is not allowed to acclimatize to external conditions before launch.

The errors for the Russian system in Table 12.6 are for pressure measurements derived from secondary radar heights rather than from pressure sensor measurements. The Russian radars compared were in an optimum state of repair. The Swiss SRS-400 measurements indicate the performance that has been achieved using a water vapour hypsometer. Both the Russian and Swiss systems are much more reliable at low pressures than at high pressures.

The consequences of the pressure errors in Table 12.6 on reported temperatures can be judged from the fact that a 1 hPa pressure error will produce a temperature error, on average, of –0.1 K at 900 hPa, –0.3 K in the upper troposphere (at 200 hPa in the tropics), ±0.5 K at 30 hPa (varying between summer and winter conditions at about 55°N) and up to at least 1K for most situations at 10 hPa.

12.8.3 *Temperature errors*

12.8.3.1 CALIBRATION

Table 12.7 summarizes the relative performance of temperature sensors at night as measured in the WMO International Radiosonde Comparison and associated tests. The results represent the typical performance averaged over a minimum of at least 15 test flights. NASA-ATM 3-thermistor measurements, using rod thermistors calibrated by VIZ Inc., have been used as an arbitrary reference. The absolute accuracy of this reference is probably about ±0.2 K. Where a range of systematic errors has been attributed to a sensor type, the range represents the spread in systematic difference found in a number of tests performed between 1984 and 1995.

Errors in temperature sensor calibration during an ascent may result from errors in factory calibration. Small changes in the sensor or in the electrical contacts

TABLE 12.7

Estimates of systematic error and sonde error (2 standard deviations) for selected temperature sensors at night from the WMO International Radiosonde Comparison and associated tests (using the performance of the NASA-ATM 3-thermistor reference as an arbitrary reference for systematic error estimates)

Temperature sensor	*System error at 300 hPa (K)*	*System error at 100 hPa (K)*	*System error at 30 hPa (K)*	*System error at 10 hPa (K)*	*Sonde error at 30 hPa (K)*	*Sonde error at 10 hPa (K)*
Thermocapacitor, aluminized Vaisala RS80	0.2 to 0.5‡ 0.2 to 0.5* 0.9 to 1.2†	0.2 to 0.5‡ 0.2 to 0.5* 1.0 to 1.3†	0.2 to 0.5‡ 0.5 to 0.8* 1.0 to 1.3†	0 to 0.3‡ 0.7 to 1.2* 1 to 1.5†	0.2	0.4
Rod thermistor, white paint VIZ	–0.3 to 0.2	–0.4 to 0.3	–0.7 to 0.3	–2.2 to –0.6	0.4	0.6
NASA-ATM 3-thermistor, VIZ calibration	reference (arbitrary)	reference (arbitrary)	reference (arbitrary)	reference (arbitrary)	0.2	0.2
Small rod thermistor, white paint, Meisei RS2-80	–0.1	0.1	–0.5	–1.2	0.3	0.6
Small rod thermistor, aluminized, Meisei RS2-91	0.1	0.1	–0.1	–0.1	0.2	0.3
Rod thermistor white paint, Russia, MRZ	0.2	0.2	–0.3	–0.8	1	1
Tungsten wire, UK RS3	–0.1 to –0.3	–0.1 to –0.3	–0.1 to –0.3	–0.1 to –0.3	0.2	0.4
Thermocouple, Switzerland SRS-400	–0.2	–0.2	–0.2	–0.2	0.3	0.5
Bimetallic spiral + radiation shield, China SMG	0.2	0.2	–0.3	–1.8	0.8	2

‡ RS80 temperatures unmodified during data processing, as in V93 correction scheme.
* RS80 temperatures modified during data processing using V86 correction scheme.
† RS80 temperatures modified during data processing using V80 correction scheme.

to the sensor and instabilities in the radiosonde transducer system and references during storage or during the ascent may also occur. Sensor or transducer drift during storage can usually be partially corrected during data processing, using adjustments based on pre-flight ground checks. In Table 12.7, the differences between the aluminized or wire sensors (i.e. Vaisala RS80 without software correction, Meisei RS2-91, UK RS3 and Switzerland SRS-400) and the reference are expected to be purely the result of calibration errors or small instabilities in the electrical connections to the sensors.

Sonde errors are only quoted for pressures of 30 hPa and 10 hPa in Table 12.7 since, for most modern temperature sensors, sonde errors show little variation between the surface and 30 hPa.

12.8.3.2 THERMAL LAG

Most current radiosonde temperature sensors (except thin wire-resistors, thermocouples and very small thermistor or thermocapacitor variables) have time constants of response that are large enough to require correction if the optimum accuracy is required. Errors from thermal lag, ϵ_τ, for a rate of ascent, V, in a uniform temperature gradient dT/dz will be given for a sensor with time constant of response, τ, by:

$$\epsilon_\tau = -\tau \cdot V \cdot dT/dz \qquad (12.8)$$

In the lower troposphere, $V \cdot dT/dz$ is often around -0.03 K s^{-1} so that a time constant of response of 3 s will lead to lag errors of around 0.1 K. In the upper troposphere, $V \cdot dT/dz$ is often around -0.05 K s^{-1} so that a time constant of response of 5 s will lead to lag errors of around 0.25 K. At much lower pressures, near 10 hPa, $V \cdot dT/dz$ in a layer 1-km thick may be about 0.015 K s^{-1} so that a time constant of response of 18 s for the temperature sensor will then lead to lag errors in mean layer temperature of about –0.3 K. In strong temperature inversions, temperature gradients may exceed 4 K per 100 m. So, for short periods during an ascent, temperature errors may be very much larger than the values quoted above for layers 1-km thick.

The time constants of response used in the examples above are typical of widely used radiosonde sensors. Bimetallic sensors and the thermistors used by Russia in the WMO Radiosonde Comparison have time constants of response that may be at least twice as large as these.

12.8.3.3 RADIATIVE HEAT EXCHANGE IN THE INFRARED

Many white paints used on radiosonde sensors have relatively high emissivity in the infrared (> 0.8). Heat exchange with the infrared background is then capable of producing significant errors in temperature measurements. The upwards infrared flux incident on the sensor is composed of emission from the surface and the atmospheric layers below the radiosonde. The downwards infrared flux is often much smaller and is composed of atmospheric emission from the layers above the radiosonde. The infrared fluxes change as the radiosonde ascends. For a given vertical temperature structure, the infrared fluxes will also vary significantly from flight to flight depending on the cloud present in the vicinity of the ascent.

If the infrared radiation emitted by the sensor is balanced by absorption of by infrared fluxes from the atmospheric environment, then the sensor is in radiative equilibrium, and will provide a correct reading. The equilibrium temperatures in situations where cloud amount is small decrease as the radiosonde ascends. In the stratosphere, radiative equilibrium temperatures are often around –60°C in conditions with low amounts of upper and middle cloud, although the precise values will change with surface temperature, surface state, and humidity in the troposphere. Thus, when stratospheric temperatures are close to –60°C, infrared errors will usually be small.

Infrared errors affect both day and night observations, although the examples considered here will be restricted to night-time measurements to facilitate the identification of the errors. The systematic errors of white thermistors in climatological averages will depend on the average air temperature and, hence, will change with latitude and average cloud cover in the larger national networks. The effects of infrared heat exchange errors at night can be seen in the measurements of the VIZ, Meisei RS2-80 and Russian thermistors in Table 12.7. At high pressures, these sensors give temperatures close to the reference, but at low pressures the temperatures reported are much colder than the reference. At pressures lower than 30 hPa in the tests considered, the radiative equilibrium temperature at night was usually significantly lower than the actual atmospheric temperatures. Therefore, the infrared radiation emitted by the temperature sensor exceeded the infrared radiation absorbed by the sensor from the atmospheric environment and the sensor cooled to a temperature lower than truth.

When atmospheric temperatures are very low, the radiative equilibrium temperature at night can be higher than the atmospheric temperature. The temperature sensor then emits less radiation than it absorbs from the atmospheric environment and the sensor will give readings higher than truth. In the tropics, positive errors of at least 0.5 K can be expected when temperatures fall below –80°C in layers around the tropopause, especially when the amounts of upper cloud are low. In tests in the British Isles, positive temperature errors larger than 0.5 K were found at pressures lower than 30 hPa on flights where air temperatures were lower than –75°C. Similar sensors had errors of about –1.7 K at 10 hPa for temperatures of -40°C at 10 hPa.

Table 12.7 shows that white rod thermistors had more variation in systematic errors at night and larger sonde errors than the Vaisala RS80 and UK RS3 sensors. This was mostly the result of variation in infrared heat exchange errors from test to test, rather than larger variations in VIZ factory calibrations. White rod thermistor errors were changed by up to 0.5 K by changes in upper cloud in a test in the United Kingdom when the atmospheric temperature structure showed little variation with time (WMO, 1994*a*). The infrared environment varies so much from flight to flight with cloud cover and surface temperature that the errors in an individual flight are extremely difficult to correct without a full radiative transfer model. For many years, a software correction was applied during data processing at night to correct infrared errors in the Vaisala RS80 radiosonde. Unfortunately, the temperature sensor had rather low emissivity in the infrared and small infrared errors. Two correction schemes were widely used (see the notes to Table 12.7), but in both cases the software resulted in a positive error in night-time temperatures.

Infrared heat exchange also influences the measurements by sensors mounted in ducts or radiation shields when the internal surfaces of the ducts are painted black. The black duct surfaces are cooled or heated by infrared radiation in a similar fashion to the white painted sensors described above. The temperature of the air passing through the duct is altered by contact with the black surfaces. Some of this air then flows over the temperature sensor. The resultant temperature error appears to be of similar sign and magnitude to the errors of the white rod thermistors (for example, see the errors for the bimetallic sensor for China SMG in Table 12.7).

12.8.3.4 HEATING BY SOLAR RADIATION

All radiosonde temperature sensors will have heating errors in daytime flights caused by incident solar radiation. Totally effective radiation shields and reflective coatings have not been achieved in practice. Thus, systematic errors due to solar radiation reaching the sensor either directly or after multiple reflection inside a radiation shield cannot be ignored. In most modern systems, software corrections are applied during data processing to compensate for the heating. These correction schemes are usually derived from special investigations of day-night differences in temperature (taking into account real diurnal variation in temperature caused by atmospheric tides) coupled with models of solar heating. The correction is then expressed as a function of solar elevation during the ascent. The correction may also take into account the actual rates of ascent, since ventilation and heating errors will change if the rate of ascent differs from the standard test conditions. At low solar elevations (less than 10°) the heating errors are extremely sensitive to changes in solar elevation. Thus, if the correction software does not update solar elevation during flight, significant errors will be generated when correcting flights during sunrise or sunset.

A simple correction scheme will only work effectively for certain cloud and surface conditions and cannot provide adequate correction for all flight conditions that might be encountered; for instance, in many ascents from coastal sites the radiosonde proceeds out to sea. In clear sky conditions, the low surface albedo of the sea will reduce backscattered solar radiation by a factor of two or three compared to average atmospheric conditions during flight. In this circumstance, software corrections based on average conditions will be too large by at least 20 per cent. On the other hand, in ascents over thick upper cloud with very high albedo, backscattering may be much larger than usual and the software correction will underestimate the required correction.

Table 12.8 contains a review of the day-night errors in the most commonly used radiosonde types. These are either the values used in software correction schemes or the actual values derived in radiosonde comparison tests that included comparisons with NASA-ATM 3-thermistor measurements. The actual values referenced to NASA measurements are likely to be accurate to ±0.2 K at high pressures and ±0.3 K at the lowest pressures.

Standardized software correction schemes as described above have an expected uncertainty of ±20 per cent. This results from possible variation in backscattered radiation caused by changes in cloud and surface albedo. The associated uncertainty in the systematic errors of temperatures corrected for solar heating will be at least ±0.2 K at 100 hPa and at least ±0.5 K at 10 hPa for the majority of sensors in Table 12.8. Sensors with solar heating two or three times smaller than the better sensors in Table 12.8 may become available within a few years. This is to be achieved by producing smaller sensors with faster response while retaining the low absorbtivity in the visible of the present sensors.

The corrections required by the Russian and Chinese systems at lower pressures are much higher than for the other systems. Many of the radiosonde types in use prior to 1980 had error characteristics similar to the Chinese sensor. The larger heating errors in the older radiosondes were caused by using sensors and supports with higher absorption at visible wavelengths than in most modern sensors. Thus, these older sensors required radiation shields. During ascent, radiosondes swing and rotate like a pendulum suspended from the balloon, so air heated by contact with either the sensor supports, internal surfaces of the radiation shields, or the radiosonde body flows over the sensor mounted in the radiation shield from time to time. This indirect heating increases rapidly as pressure decreases in the stratosphere.

Solar heating of most of the sensors (apart from the tungsten wire and thermocouple sensors in Table 12.8),

TABLE 12.8

Day-night temperature differences for selected radiosonde sensor types and estimates of daytime sonde temperature errors (2 standard deviations), for solar elevations higher than 20°

Temperature sensor	*Day-night system differences at 300 hPa (K)*	*Day-night system differences at 100 hPa (K)*	*Day-night system differences at 30 hPa (K)*	*Day-night system differences at 10 hPa (K)*	*Daytime sonde error at 30 hPa (K)*	*Daytime sonde error at 10 hPa (K)*
Thermocapacitor, aluminized Vaisala RS80	0.9	1.3	2.2	2.8*	0.6	1
†Rod thermistor, white paint VIZ	0.4	1	1.6	2.5	0.8	1.2
Small rod thermistor, white paint, Meisei RS2-80	0.3*	0.8*	1.6*	2.3*	0.8	1.1
Small rod thermistor, aluminized Meisei RS2-91	0.6*	1.3*	2.0*	2.5*	0.9	1.3
Rod thermistor, white paint Russia, MRZ	1*	1.8*	3.3	5.1	1.2	1.4
Tungsten wire UK RS3	0.4	0.9	1.7	2.6	0.5	0.8
†Thermocouple Switzerland SRS-400	0.4	0.9	1.4	1.8	0.6	0.8
Bimetallic spiral radiation shield China SMG	0.8*	1.3*	3.4*	9.9*	1.4	3

† Measurements are not usually software corrected before issue to users, as of May 1996.

* Values used in software correction scheme during the WMO International Radiosonde Comparison; other values estimated from direct comparisons with NASA-ATM 3-thermistor measurements.

also varies significantly with the orientation of the sensor with respect to the Sun. Variations in the orientation from flight to flight, as well as variations in the backscattered radiation from flight to flight produce sonde errors for all the radiosondes that are larger for daytime than for night-time.

12.8.3.5 DEPOSITION OF ICE OR WATER ON THE SENSOR

Another source of temperature error is the deposition of water or ice on the temperature sensor. This will lead to psychrometric cooling (from the wet-bulb effect) of the temperature sensor, once atmospheric relative humidity drops to less than 100 per cent later in the ascent. If the sensor tends to collect water or ice, rather than rapidly shed the precipitation, large parts of the temperature measurements during the ascent may be corrupted. At night, a coating of ice causes an aluminized sensor to act like a black sensor in the infrared, leading to large cooling at low pressures in commonly encountered conditions.

Furthermore, if water deposited on the sensor freezes as the sensor moves into colder air, the latent heat released will raise the temperature towards 0°C. If a sensor becomes coated with ice and then moves into a warmer layer, the temperature will not rise above 0°C until the ice has melted. Thus, isothermal layers reported close to 0°C in wet conditions should be treated with some caution.

12.8.4 *Relative humidity errors*

12.8.4.1 CALIBRATION

Errors in relative humidity measurements may occur because of changes in calibration during storage. This problem is likely to be more acute with relative humidity sensors than for temperature or pressure sensors. The manufacturer's instructions regarding the storage of the sensors and preparations for use must not be ignored.

During manufacture, calibrations on individual sensors are often only performed at a few (less than three) pre-set relative humidity points, and possibly only at one temperature (see for example, Wade, 1995). In many cases, the temperature dependence of the sensor calibration is not checked individually, or in batches, but is again assumed to follow curves determined in a limited number of tests. Sensor calibrations often vary by several per cent in relative humidity from batch to batch, as can be seen from measurements in low level cloud (Nash, Elms and Oakley, 1995). This may be a consequence of faulty calibration procedures during manufacture, for instance actual sensor performance in a given batch may differ from the standardized calibration curves fitted to the pre-set humidity checks. On the other hand, it could be the result of batch variation in the stability of sensors during storage.

Table 12.9 summarizes the systematic differences between the most widely used sensors tested during the WMO International Radiosonde Comparison. More detailed results may be found in Nash, Elms and

TABLE 12.9

Systematic differences and sonde error (2 standard deviations) for various relative humidity sensors, at night (ascents through low cloud excluded) for temperatures higher than –20°C, taken from the WMO International Radiosonde Comparison and other associated tests

(The reference is based on an assumed error pattern for Vaisala RS80, A-Humicap measurements)

Humidity sensor	*Systematic differences (80–90 per cent R.H.) (% R.H.)*	*Systematic differences (40–60 per cent R.H.) (% R.H.)*	*Systematic differences (10–20 per cent R.H.) (% R.H.)*	*Sonde error (80–90 per cent R.H.) (% R.H.)*	*Sonde error (40–60 per cent R.H.) (% R.H.)*	*Sonde error (10–20 per cent R.H.) (% R.H.)*
Thin-film capacitor, Vaisala RS80, A-Humicap	–2 (assumed)	–1 (assumed)	0 (assumed)	6	6	4
Thin-film capacitor, Vaisala RS80, H-Humicap	–1	0	0	6	6	4
Thin-film capacitor, Meisei RS2-91	–9	1	–4	8	6	4
Carbon hygristor, VIZ MkII	6	0	5	8	8	12
Carbon hygristor, Meisei RS2-80	–8	–4	9	8	6	8
Carbon hygristor, VIZ 1392	4	-3	10	8	8	12
Goldbeater's skin sensor, Russia + UK	–8	–1	7	12	18	16
Lithium chloride, India, MK III, 1985	–7	–7	12	20	20	22

Oakley (1995). Comparisons have been limited to flights where the radiosondes have not passed through low level cloud. The sensors will not have become wet or contaminated by precipitation. The results shown here have also been limited to night flights to eliminate complications caused by solar heating.

The comparisons in Table 12.9 have been limited to temperatures above –20°C. Here, the time constants of response of the thin-film capacitor and the carbon hygristor are similar and fast enough to avoid significant systematic bias from slow sensor response. Goldbeater's skin and lithium chloride are able to respond reasonably well to rapid changes in relative humidity at these temperatures, although the very slow sensor response at high and low humidities will have contributed to the systematic differences shown in Table 12.9.

The performance of the Vaisala RS80 A-Humicap was used as an arbitrary reference linking the tests in Table 12.9. An error distribution has been assumed for the sensor, based on laboratory tests of a limited number of sensors and operational measurement quality in low-level clouds. It would be unwise to assume that the assumed average performance for the arbitrary reference fell closer than ±3 per cent relative humidity to the actual absolute errors of the radiosonde measurements. The H-Humicap is a more recent sensor development that is expected to have improved long-term calibration stability when exposed to high humidity.

The VIZ MkII carbon hygristor is a smaller sensor than the carbon hygristor used in the VIZ 1392 radiosonde. The two sensors use different algorithms to describe the calibration of the sensors, as issued from the manufacturer.

The results in Table 12.9 indicate that for several widely used sensors, the typical calibration curves used for many years need to be reviewed, particularly at high and low humidities (see also Garand, *et al.*, 1992). Many algorithms used to describe sensor performance are now being revised (see for example, Wade, 1994), since automated data processing allows more complex algorithms to be used to represent sensor calibration. In the case of the Meisei thin-film capacitor, the low bias at high relative humidity has subsequently been found to result from a change in calibration of the sensor during storage.

The calibration accuracy at high humidity is essential for users who wish to input radiosonde information into numerical weather prediction models. The calibration accuracy at low relative humidity is of greater importance for climatology and scientific research. Sensor calibration has also been examined in detail in the WMO Radiosonde Relative Humidity Sensor Comparison performed in 1995 (to be published).

In order to obtain good quality operational measurements, operators need to check the operational performance of relative humidity sensors carefully while preparing for launch. They should also keep records of the relative humidity reported when radiosondes pass through cloud layers at low levels. This information needs to be fed back to the suppliers so that corrective action can be taken if sensor calibration is clearly deficient at high humidity.

Humidity sonde errors are often not constant over the whole relative humidity range. Vaisala sensor calibration used during flight is adjusted by using a ground check at very low humidity just before launch. Therefore, the Vaisala measurements are more reproducible from flight to flight at low relative humidity. On the other hand, the calibration procedures with carbon hygristors tend to ensure optimum accuracy at close to 30 per cent relative humidity. Sonde errors for VIZ carbon hygristors are often larger at very low relative humidity than at medium and high humidities. The sonde errors of lithium chloride and goldbeater's skin sensors are larger than the other sensors, partly because of the slow speeds of response and hysteresis errors considered in the next section.

12.8.4.2 SLOW SENSOR RESPONSE AND SENSOR HYSTERESIS

From Table 12.5 it will be seen that the speed of response of nearly all humidity-sensing materials is less than optimum at low temperatures in the upper troposphere. At higher temperatures in the troposphere, the response speeds of sensors, such as goldbeater's skin and lithium chloride, are also too slow to avoid systematic bias in dry or wet layers. However, slow time constants of response may only start to introduce a significant systematic bias in measurements by thin-film capacitors and carbon hygristors at temperatures lower than about –20°C. The carbon hygristor response becomes extremely slow at temperatures lower than –40°C.

Thin-film capacitors can sustain useful measurement capability to temperatures lower than –40°C, even though the reliability of calibration deteriorates to some extent at the lowest temperatures. For instance, for a relative humidity between 20 and 60 per cent, the Vaisala H-Humicap type thin-film capacitor sensors at –50°C report relative humidity values that are 10 per cent higher than the Vaisala A-type thin-film capacitors. The same sensors agree within a few per cent at higher temperatures (see Table 12.9). The standard deviation of the differences between the measurements by the two types of sensors at –50°C for this relative humidity range is found to be around 4 per cent.

As relative humidity can rise to very high values and then fall to low values several times during an ascent, sensor hysteresis is also more of a problem than with pressure or temperature sensors. In many sensors, hysteresis errors are limited to a few per cent relative humidity, but errors may be larger for a sensor, such as goldbeater's skin. Hysteresis errors are only partially alleviated by thoroughly seasoning the sensors during manufacture.

12.8.4.3 DIFFERENCES BETWEEN SENSOR TEMPERATURE AND TRUE ATMOSPHERIC TEMPERATURE

The dewpoint reported in the radiosonde TEMP message is derived from the water vapour pressure at a given time into flight. This water vapour pressure is usually obtained by multiplying the saturated vapour pressure computed from the radiosonde temperature by the radiosonde relative humidity measurement. If the temperature of the relative humidity sensor does not correspond to the temperature reported by the radiosonde, then the reported dewpoint will be in error. This will occur, either during the day or at night, if the thermal lag of the relative humidity sensor is significantly larger than that of the temperature sensor. If the sensor temperature lags the true atmospheric temperature by 0.5 K at a temperature close to 20°C, then the relative humidity reported by the sensor will be about 97 per cent of the true relative humidity. This will result in an error of –1.5 per cent at a relative humidity of 50 per cent. As temperature decreases to –10°C and then to –30°C, the same temperature lag in the sensor causes the reported relative humidity to decrease to 96 per cent and then to 95 per cent of the true value.

During daytime flights, direct heating by solar radiation can also produce significant heating of the relative humidity sensor. In addition, the sensor may be heated indirectly by air that has previously flown over contact protective covers or duct walls heated directly by solar radiation. Brousaides and Morrissey (1974) quantified the errors that could occur with VIZ radiosondes. Cole and Miller (1995) investigated the errors that could occur when Vaisala RS80 radiosondes were launched from poorly ventilated shelters in the tropics.

The daytime differences between carbon hygristor and thin-film capacitor measurements obtained in the WMO International Radiosonde Comparison were very close to the values obtained at night. Thus, while both sensor types must have some negative error caused by direct or indirect solar heating of the relative humidity sensor, the errors were of similar magnitude for both types of sensor. The solar heating of goldbeater's skin sensors may be larger. At temperatures around –30°C, daytime goldbeater's skin measurements (referenced to the thin-film capacitors) were about 90 per cent of the expected relative humidity values, although at temperatures near 0°C the effects of additional heating could not be clearly identified.

12.8.4.4 WETTING OR ICING IN CLOUD

When the performance of relative humidity sensors is compared after passing through low cloud or fog (where the external temperature sensors have clearly become wet), the systematic differences between the sensor measurements are not close to those shown in Table 12.9. In particular, the systematic differences between the Vaisala thin-film capacitor and VIZ carbon hygristor measurements at a relative humidity from 0 to 70 per cent increase the relative humidity by at least 10 per cent on average (Nash, Elms and Oakley, 1995). Both of these sensor types have possible additional errors in wet conditions, although the mechanisms causing the additional errors are quite different for the two types.

Vaisala thin-film capacitors, together with the protective covers for the sensor, usually become contaminated to some extent in low cloud. On emerging from cloud in severe icing conditions, the sensors may report a relative humidity that is high by up to 30 per cent. Positive errors from sensor contamination are more usually in the range from 1 to 20 per cent relative humidity. In some cases, the contamination may only last for a few minutes, but in others, the contamination can continue to affect measurements into the upper stratosphere. It is hoped that heating the sensors during the ascent could eliminate the contamination more quickly in future sensors.

The VIZ carbon hygristor calibrations are not very stable when the sensors are exposed to high relative humidity for long periods of time in the laboratory. If the sensors become wet during an ascent or if they are exposed to very moist conditions, it appears that the calibration often changes on emerging from the cloud. The effect of the change in calibration is to cause the relative humidity reported in the remainder of the flight to fall by between 1 and 15 per cent, on average, compared to relative humidity reports in dry conditions.

Hence, relative humidity measurements in the upper troposphere after ascents have passed through cloud layers in the lower troposphere need to be treated with more caution than measurements made in dry conditions.

12.8.5 *Software errors*

There are a large number of software errors or omissions that can be made in a radiosonde ground system. Testing must be extensive before the software is introduced into operational service.

Operators at radiosonde stations should be alert for indications of wrong results. Some errors may occur only during certain meteorological circumstances. Thus, it may be necessary to gather evidence over many ascents before the nature of the errors or omissions become apparent. Comprehensive interactive data displays for the operator and comprehensive archives of the incoming radiosonde information are essential if fault finding is to be efficient.

12.9 Comparison, calibration and maintenance

12.9.1 *Comparisons*

The overall quality of operational radiosonde geopotential height measurements (and hence temperature measurements averaged through thick layers) is monitored by comparison to geopotential heights at standard pressures with short-term (six-hour) forecasts from global numerical weather prediction models for the same location. The statistics are summarized into monthly averages that are used to identify both sub-standard measurement quality and significant systematic changes in radiosonde performance. The European Centre for Medium Range Weather Forecasts in Reading is the lead centre currently designated by the Commission for Basic Systems for this work, but other national forecast centres also produce similar statistics.

Random errors in geopotential height (and hence temperature) measurements can also be identified at individual stations from analyses of the changes in time-series of measurements of geopotential height, at 100 hPa or lower pressures, where atmospheric variability is usually small from day to day. The compatibility between the results from this method and those from comparison with short-term forecast fields are provided in WMO (1988*a*).

The performance of radiosondes or radiosonde sensors can be investigated in the laboratory with suitably equipped test chambers, where temperature and pressure can be controlled to simulate radiosonde flight conditions.

Detailed investigations of temperature, pressure, and relative humidity sensor performance in flight are best performed using radiosonde comparison tests, where several radiosonde types are flown together on the same balloon ascent. When testing a new radiosonde development, it is advisable to have at least two other types of radiosonde with which to compare the newly developed design. The error characteristics of the other radiosondes should have been established in earlier tests. An ideal comparison test site would have an independent method of measuring the heights of the radiosondes during flight. This can be achieved by using measurements with a high precision radar (or a global positioning system engine capable of accurate height measurements when flown with the radiosondes). A reliable height measurement allows reliable estimates of the systematic bias in pressure sensor measurements. This is an advantage since the systematic errors of many widely used pressure sensors vary to some extent with the conditions during ascent and with the age of the sensors.

12.9.1.1 QUALITY EVALUATION USING SHORT-TERM FORECASTS

For the better global numerical weather prediction models, the random error in short-term (six-hour) forecasts of 100 hPa geopotential heights is between 10 and 20 m in most areas of the world. These errors correspond to a mean layer temperature error from the surface to 100 hPa of between 0.15 and 0.3 K. Thus, the comparison with the forecast fields provides good sensitivity in detecting sonde errors in temperature, if sonde errors are greater than about 0.3 K. Forecast fields rather than analysis fields are used as the reference in this comparison. Forecast fields provide a reference that is less influenced by the systematic errors in geopotential heights of the radiosonde measurements in the area than the meteorological analysis fields. However, six-hour forecast fields will have small systematic errors and should not be considered as an absolute reference. Uncertainty in the systematic error of the forecast field is at least ±10 m at 100 hPa. The systematic differences of forecasts from the measurements of a given radiosonde station vary between forecast centres by at least this amount. In addition, systematic errors in forecast fields may also change with time by similar amounts, when forecast models and data assimilation techniques are improved. None the less, comparisons with the forecast fields at the lead centres for operational monitoring give clear indications of those radiosonde stations and radiosonde types where there are large systematic errors in the radiosonde reports. WMO (1993*b*) provides the most recent review of radiosonde errors in the global network for heights up to 30 hPa.

12.9.1.2 QUALITY EVALUATION USING ATMOSPHERIC TIME-SERIES

Random errors in radiosonde measurements can be estimated from the time-series of closely-spaced measurements of geopotential heights, at pressure levels where the geopotential heights only change slowly with time. Suitable pressure levels are 100, 50, or 30 hPa. For radiosonde observations made at 12-hour intervals, this is achieved by computing the difference between the observation at +12 h, and a linear interpolation in time between the observations at 0 and +24 h. Further differences are, then, computed by incrementing in steps of 24 hours through the time-series. An estimate of the random errors in the radiosonde measurements can then be derived from the standard deviation of the differences. For much of the year, this procedure is of similar sensitivity to the comparison made with forecast fields. One exception may be during winter conditions at middle and high latitudes, when the geopotential heights at 100 hPa will sometimes change very rapidly over a short time.

The average values of the differences from the time-series may provide information on the day-night differences in radiosonde temperature measurements. Interpretation of day-night differences must allow for real daily variation in geopotential height caused by diurnal and semidiurnal tides. Real day-night differences at mid-latitudes for 100 hPa geopotential heights can be as large as 30 m between observations at 1800 and 0600 local time (Nash, 1984), whereas real day-night differences between observations at 1200 and 0000 local time will usually be in the range 0 ± 10 m.

It is beneficial if individual radiosonde stations keep records of the variation in the time-series of geopotential height measurements at 100 hPa and in the geopotential height increment (100–30) hPa. This allows the operators to check for large anomalies in measurements as the ascent is in progress.

12.9.1.3 Radiosonde comparison tests

Radiosonde comparison tests allow the performance of the pressure, temperature, and relative humidity sensors on the radiosonde to be compared independently as a function of time.

Laboratory tests will be performed in facilities that are similar to those required for detailed calibration of the radiosondes by the manufacturer. These tests can be used to check the adequacy of radiosonde calibration, for example the dependence of calibration on sensor temperature. However, in the laboratory, it is difficult to simulate real atmospheric conditions for radiative errors and wetting or icing of sensors. Errors from these sources are best examined in comparisons made during actual ascents.

The comparison of measurements during actual ascents requires that timing of the samples for the different systems be synchronized as accurately as possible, ideally to better than ±1 s. In recent years, software packages have been developed to support WMO Radiosonde Comparison tests (WMO, 1996*a*). These allow all the radiosonde samples to be stored in a comparison database and to be compared by the project scientists immediately following a test flight. It is important that comparison samples are reviewed very quickly during a test. Any problem with the samples caused by test procedures (for example interference between radiosondes) or faults in the radiosondes can, then, be identified very quickly and suitable additional investigations initiated. The software also allows the final radiosonde comparison statistics to be generated in a form that is suitable for publication.

Initial tests for new radiosonde designs may not merit large numbers of comparison flights, since the main faults can be discovered in a small number of flights. However, larger scale investigations can be justified once systems are more fully developed. As the reproducibility of the measurements of most modern radiosondes has improved, it has become possible to obtain useful measurements of systematic bias in temperature and pressure from about 10 to 15 flights for one given flight condition (for instance, one time of day). It is unwise to assume that daytime flights at all solar elevations will have the same bias, so tests are best organized to produce at least 10 to 15 comparison flights at a similar solar elevation. The measurements of temperature sensor performance are best linked to other test results by comparisons performed at night. The link should be based on measurements from radiosondes with wire or aluminized sensors and not from sensors with significant infrared heat exchange errors. If a continuous series of comparison flights (alternating between day and night) can be sustained, then it is possible to use the atmospheric time-series technique to estimate the magnitude of day-night differences in temperature measurements.

As noted earlier, the most extensive series of comparison tests performed in recent years were those of the WMO International Radiosonde Comparison. Initial results have been published in WMO (1987; 1991; 1996*b*). The results from these tests were the basis of the information provided in Tables 12.6 to 12.9.

The first international comparison of radiosondes was held at Payerne, Switzerland in 1950. Average systematic differences between radiosonde pressures and temperatures were 4 hPa and 0.7 K, with random errors (2 standard deviations) of 14 hPa and 2 K. These values should be compared with the results for modern systems in Tables 12.6 to 12.8. The results from a second comparison carried out at the same site in 1956 showed that accuracy needed to be improved by the application of radiation corrections to the temperature readings. The errors in pressure and temperature at the 50-hPa level were quite large for most radiosondes and increased rapidly at higher levels, especially during daylight. In 1973, a regional comparison was held in Trappes, France. This identified significant calibration errors in some radiosondes, with one bimetallic temperature sensor with a radiation error as large as 10 K.

12.9.2 *Calibration*

The methods of calibration used by manufacturers should be identified before purchasing radiosondes in large numbers. The quality control procedures used to ensure that measurement accuracy will be sustained in mass production must also be checked for adequacy. Purchasers should bear in mind that certain specified levels of error and product failure may have to be tolerated if the cost of the radiosonde is to remain acceptable. However, failure rates of radiosondes in flight should not be higher than 1 or 2 per cent from reliable manufacturers.

Unless radiosonde sensors can be produced in large batches to give the reproducibility and accuracy required by users, it is necessary to calibrate the instruments and sensors individually. Even if the sensors can be produced in large batches to meet an agreed set of standardized performance checks, it is necessary for representative samples, selected at random, to be checked in more detail. The calibration process should, as far as possible, simulate flight conditions of pressure and temperature. Calibrations should normally be performed with falling pressure and falling temperature. Relative humidity will probably be checked in a separate facility. The reference sensors used during calibration should be traceable to national standards and checked at suitable intervals in standards laboratories. The references should be capable of performing over the full temperature range required for radiosonde measurements.

The design of the calibration apparatus depends largely on whether the complete radiosonde must be calibrated as a unit or on whether the meteorological units can be tested while separated from the radiosonde transmitter. In the latter case, a much smaller apparatus can be used. The calibration facility should be adequate to cover the range of pressure and temperature likely to be encountered in actual soundings. It should be possible to maintain the conditions in the calibration chamber stable at any desired value better than ±0.2 hPa min^{-1} for pressure, ±0.25 K min^{-1} for temperature and 1 per cent relative humidity per minute. The conditions in the calibration chamber should be measured with systematic errors less than ±0.2 hPa for pressure, ±0.1 K for temperature and ±1 per cent relative humidity. Reference thermometers should be positioned in the calibration chamber in order to identify the range of temperature in the space occupied by the sensors under calibration. The range of temperatures should not exceed 0.5 K. Sufficient measurements should be made to ensure that the calibration curves represent the performance of the sensors to the accuracy required by the users. Pressure sensors that are not fully compensated for temperature variations must be calibrated at more than one temperature. Thus, it may be an advantage if the temperature calibration chamber is also suitable for the evaluation of the pressure units.

Humidity calibration is usually carried out in a separate apparatus. This can take place in a chamber in which a blower circulates air rapidly past a ventilated psychrometer or dew point hygrometer and then through one of four vessels containing, respectively, warm water, saturated solutions of sodium nitrate and calcium chloride, and silica gel. Any one of these vessels can be introduced into the circulation system by means of a multiple valve, so that relative humidities of 100, 70, 40 and 10 per cent are readily obtained. The standard deviation of the variation in relative humidity should not exceed one per cent in the space occupied by the units under calibration.

An alternative arrangement for humidity calibration is a duct or chamber ventilated with a mixture of air from two vessels, one kept saturated with water and the other dried by silica gel, the relative humidity of the mixture being manually controlled with a valve regulating the relative amounts passing into the duct.

Because of the importance of type or batch calibration of radiosondes, the Commission for Instruments and Methods of Observation[3] urges Members to test, nationally or regionally, selected samples of radiosondes under laboratory conditions in order to ensure that the calibrations supplied by the manufacturer are valid.

12.9.3 *Maintenance*

Failure rates in the ground system should be low for radiosonde systems based on modern electronics, as long as adequate protection against lightning strikes close to the aerials is provided. The manufacturer should be able to advise on a suitable set of spares for the system. If a module in the ground system fails, it would normally be replaced by a spare module, while the faulty module is returned for repair.

The maintenance requirements for radiosonde systems relying on radar height measurements to replace radiosonde pressure measurements are quite different. In this case, local maintenance should be readily available throughout the network from staff with good technical capability (both mechanical and electrical). This will be essential if accurate tracking capability is to be retained and if long-term drifts in systematic errors in height are to be avoided.

12.10 Computations and reporting

There are no prescribed standardized procedures for the computation of radiosonde observations. The main issue is the selection of levels to reproduce accurately and efficiently the temperature and humidity profile against geopotential from the radiosonde data. Guidance is given in WMO (1986) and in the coding procedures agreed by WMO (1995) (Code FM 35-X Ext. TEMP).

12.10.1 *Radiosonde computations and reporting procedures*

Upper air measurements are usually input into numerical weather forecasts as a series of layer averages, the thickness of the layers depending on the scales of atmospheric motion relevant to the forecast. The layers will not necessarily be centred at standard pressures or heights, but will often be centred at levels that vary as the surface pressure changes. Thus, the variation in temperature and relative humidity between the standard levels in the upper air report must be reported to sufficient accuracy to ensure that the layer averages used in numerical forecasts are not degraded in accuracy by the reporting procedure.

A large number of national practices for reporting relative humidity were introduced in the past to cope with deficiencies in the sensors in use at that time. In some national networks, a relative humidity lower than 20 per cent was not reported in TEMP messages. It is now clear from Raman lidar and frost point hygrometer measurements that a relative humidity lower than 20 per cent is realistic and quite common in the troposphere. In many countries, a relative humidity was not reported when temperatures were lower than –40°C. These practices were usually justified on the basis of the performance of the relative humidity sensors at the time. Recent progress with relative humidity measurements requires that many of these reporting limitations be revised or eliminated.

Prior to 1980, most radiosonde measurements were processed manually by the operators by using various computational aids. These methods were based on the selection of a limited number of significant levels to represent the radiosonde measurement, possibly about 30 significant levels for a flight up to 30 km. The WMO codes reflected the difficulties of condensing a large amount of information on vertical structure into a short message by manual methods. The coding rules allowed linear interpolations in height between significant levels to differ from the original measurements by up to ±1 K

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[3] Recommended by the Commission for Instruments and Methods of Observation at its eleventh session, 1993, through Recommendation 9 (CIMO-XI).

for temperature and up to ±15 per cent for relative humidity in the troposphere and up to ±2 K for temperature in the stratosphere. It was expected that operators would not allow large interpolation errors to persist over deep layers in the vertical.

In modern radiosonde ground systems, the use of cheap but powerful computing systems means that much higher sampling rates can be used for archiving and processing the radiosonde measurements than with manual computations. The manual processing of radiosonde measurements nearly always introduces unnecessary errors in upper air computations and should be eliminated as soon as possible.

However, the automation of the selection procedure for significant levels for the TEMP messages is not straightforward. The available algorithms for automated upper air message generation often have significant flaws. For instance, when there are few pronounced variations in relative humidity in the vertical, automated systems often allow large temperature interpolation errors to extend over several kilometres in the vertical. Furthermore, the algorithms often allow large systematic bias between the reported relative humidity structure and the original measurements over layers as thick as 500 m. This is unacceptable to users, particularly in the atmospheric boundary layer and when the radiosonde passes through clouds. Interpolation between significant cloud levels must fit close to the maximum relative humidity observed in the cloud.

Therefore, reports from automated systems need to be checked by operators to establish whether coding procedures are introducing significant systematic bias between the upper air report and the original radiosonde measurements. Additional significant levels may have to be inserted by the operator to eliminate unnecessary bias. TEMP messages with acceptable systematic errors are often produced more easily by adopting a national practice of reducing the WMO temperature fitting limits to half the magnitude cited above. Alternatively, the advent of improved meteorological communications should allow the approximation in reporting upper air observations to be reduced by reporting measurements using the appropriate BUFR code message.

12.10.2 *Corrections*

As should be clear from earlier sections, the variation in radiosonde sensor performance caused by the large range of conditions encountered during a radiosonde ascent is too large to be represented by a simple calibration obtained at a given temperature. Modern data processing allows more complex calibration algorithms to be used. These have provided measurements of better accuracy than achieved with manual systems. It is vital that these algorithms are adequately documented. Users should be informed when significant improvements or modifications to the algorithms occur. Records archived in radiosonde stations should include the radiosondes in use and the critical algorithms used for data processing.

All radiosonde temperature measurements have radiation errors. In most cases, these cannot be compensated perfectly because the errors depend on the cloud distribution, surface state, the orientation of the radiosonde during the ascent, and solar elevation. Most users outside the Meteorological Services are unaware of the usual error characteristics of the national radiosonde sensors in use. Therefore, it is recommended that a radiation correction (based on expected sensor performance in usual conditions) should always be applied during data processing. The details of this radiation correction should be recorded and kept with the station archive, along with an adequate archive of the original raw radiosonde observations, if required by national practice.

Errors from infrared heat exchange pose a particular problem for correction, since the errors are not independent of atmospheric temperature. Solar heating errors for metallic (for example, aluminized) sensors and white-painted sensors are similar (see Table 12.8). Thus, it is preferable to eliminate the use of white paint with high emissivity in the infrared as a sensor coating as soon as possible, rather than to develop very complex correction schemes for infrared heat exchange errors.

Similarly, it is unwise to attempt to correct abnormally high solar radiation heating errors by software, rather than to eliminate the additional sources of heating by positioning the sensor correctly with respect to its supports, connecting leads, and radiosonde body.

Considering the importance of the ways in which corrections are applied, the Commission for Instruments and Methods of Observation[4] urges Members to:

(*a*) Correct and make available the corrected upper air data from the various GOS upper air stations;

(*b*) Make users of the data aware of changes in the methodology used to correct reports, so that they may be adjusted, if desired;

(*c*) Archive both the corrected and uncorrected upper air observations and produce records for climatological applications of the correction applied. The method used should be determined nationally;

(*d*) Inform WMO of the method of correction applied.

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[4] Recommended by the Commission for Instruments and Methods of Observation at its eleventh session, 1993, through Recommendation 8 (CIMO-XI).

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ANNEX 12.A

ACCURACY REQUIREMENTS (STANDARD ERROR) FOR UPPER AIR MEASUREMENTS FOR SYNOPTIC METEOROLOGY, INTERPRETED FOR CONVENTIONAL UPPER AIR AND WIND MEASUREMENTS

Variable	*Range*	*Accuracy requirement*
Pressure	From surface to 5 hPa	±1 hPa
Temperature	From surface to 100 hPa	±0.5°C
	100 to 5 hPa	±1°C
Relative humidity	Troposphere	±5 % (RH)
Wind direction	From surface to 100 hPa	±5°, for less than 15 m s^{-1} ±2.5° at higher speeds
	From 100 to 5 hPa	±5°
Wind speed	From surface to 100 hPa	±1 m s^{-1}
	From 100 to 5 hPa	±2 m s^{-1}
Geopotential height of significant level	From surface to 100 hPa	±1 per cent near the surface decreasing to ±0.5 per cent at 100 hPa

ANNEX 12.B

PERFORMANCE LIMITS FOR UPPER WIND AND RADIOSONDE TEMPERATURE, RELATIVE HUMIDITY AND GEOPOTENTIAL HEIGHT

TABLE 1

Summary of performance limits for wind-sounding equipment

Limit (*a*) — the limit of error beyond which improvement is unnecessary for the stated purpose.

Limit (*b*) — the limit of error beyond which the data obtained will have negligible value for the stated purpose.

(Values vary substantially with season and location; errors are standard vector errors in m s^{-1} except where otherwise noted)

For study of mesoscale systems at all levels and locations a lower limit (a) of 0.5 m s^{-1} seems appropriate											
Region	*Pressure level (hPa)*	*Height (km)*	*Local use*		*Synoptic use*		*Climatological use*		*Wind strength in which sounding equipment must be able to operate*		*Remarks*
			(a)	*(b)*	*(a)*	*(b)*	*(a)*	*(b)*	*(a)*	*(b)*	
Extratropical troposphere			0.8	6	1	4	1	5[3]	40[4]	18[4]	In particular localities, operation in winds of 50 m s^{-1} in the lower troposphere and 150 m s^{-1} near the tropopause may be called for
			increasing to		increasing to		increasing to		increasing to		
			1.5	10[1]	2	7[2]	2	10[3]	80[4]	37[4]	
			near the tropopause		near the tropopause		near the tropopause		near the tropopause		
Equatorial troposphere			0.8	4	1	3	1	5[8]	20	10	Ignores requirement for soundings in tropical cyclones
			increasing to		increasing to		increasing to		increasing to		
			1.5[5]	7[6]	2	6[7]	2	5[8]	60	40	
			near the tropopause		near the tropopause		near the tropopause		near the tropopause		
Extratropical stratosphere	50	20	0.7	3[9]	0.7	5[10]	0.7	Vary variable with season, altitude and location	75[11]	Not specified	
	30	24	0.7	2	0.7	3.6	0.7				
	10	31	1	3	1	5.5	1		100[11]		
	5	36	1.2	3	1.2	7	1.2				
	0.7	50	(1.5)	4	(1.5)	13	(1.5)		200		
Equatorial stratosphere	50	20	0.7	5	0.7	5	0.7	5	40[12]	Not specified	For research purposes, there is a need for wind profiles with high vertical resolution and as small observational errors as practical
	30	24	0.7		0.7		0.7				
	10	31	1	5	1	5	1	5	45[12]		
	5	36	1.2		1.2		1.2				
	0.7	50	1.5	10	1.5	10	1.5	10	100[12]		

NOTE: Unless otherwise specified, values refer to wind measurements averaged over a layer 300 to 400 m thick in the troposphere and 600 to 800 m thick in the stratosphere, centred on the reporting level.

NOTES TO TABLE 1

1. Least stringent limit (*b*) is 30 m s^{-1} (winter, North Atlantic).
2. Least stringent limit (*b*) is 20 m s^{-1} (winter, North Atlantic).
3. These limits relate to least stringent limits (*b*) for the systematic part of the error. Corresponding values for the standard vector deviation of the random part of the error are 10 m s^{-1} increasing to 15 m s^{-1} near the tropopause. More stringent limits (*b*) are appropriate in many areas where large quantities of good quality data already exist.
4. For mean wind 0–40 000 feet (0–12 km) in winter; over southern England limit (*a*) is 60 m s^{-1} and limit (*b*) is 27 m s^{-1}; over southern Japan, where the most severe conditions occur, limit (*a*) is 80 m s^{-1} and limit (*b*) is 50 m s^{-1}.
5. Perhaps little or no increase with height occurs over substantial areas, giving a limit (*a*) of 1 m s^{-1} in the high troposphere.
6. Least stringent limit (*b*) is 15 m s^{-1} (mostly in winter near the boundary of the tropics).
7. Least stringent limit (*b*) is 12 m s^{-1} (mostly in winter near the boundary of the tropics).
8. These are the least stringent limits (*b*) for the systematic part of the error. Corresponding values for the standard vector deviation of the random part are 5 m s^{-1} increasing to 10 m s^{-1} in the upper troposphere.
9. Least stringent limits (*b*) in winter are 11 and 13 m s^{-1} at 50 and 30 hPa, respectively, 20 to 25 m s^{-1} at 10 to 5 hPa and even larger values at 1 hPa. These values relate to short-period (single month) means; still larger values relate to long-period means (e.g. periods involving several winters) but distributions in such samples are apt to be multi-model.
10. Least stringent limits (*b*) in winter are 6, 7, 10, 12 and 16 m s^{-1} at 50, 30, 10, 5 and 0.7 hPa, respectively.
11. For mean wind 0–100 000 feet (0–30 km) in the worst season (winter) over southern England, limit (*a*) is 45 m s^{-1} and limit (*b*) is 26 m s^{-1}.
12. These maximum winds at individual levels do not occur simultaneously at all levels. These values are estimates of the strongest individual winds likely to be encountered during the periods when the "26-month" and annual oscillations combine to yield the strongest average winds. Mean winds through deep layers will be substantially less than these values because of low interlevel correlations over deep layers.

TABLE 2
Summary of performance limits for aerological temperature sounding

Limit (*a*) — the standard error of temperature below which improvement is unnecessary for the stated purpose.
Limit (*b*) — the limit of error beyond which the data obtained will have negligible value for the stated purpose.
(Most values vary substantially with location and season; errors are standard errors
in °C except where otherwise indicated)

Region	*Pressure level (hPa)*	*Height (km)*	*Local use*		*Synoptic use*		*Climatological use*		*Range of temperature*	*Remarks*
			(*a*)	(*b*)	(*a*)	(*b*)	(*a*)	(*b*)		
Extratropical troposphere			0.15	3.0[1] (2.0 from 30° to 40° latitude)	0.15	2.0	0.15	2.0[2]	–80 to +40	
Equatorial troposphere	Lower troposphere		0.15	1.0	0.15	0.7	0.15	1.0[2]	–100 to +40	
	Upper troposphere		0.15	1.5	0.15	1.0	0.15	1.5[2]		
Extratropical stratosphere	200		0.3	4[3]	0.3	3.8	0.3	1.5[6]	–100 to +50	
	100		0.3	3	0.3	1.4	0.3	1.5		
	50		0.3	1.5	0.3	0.7	0.3	1.5		
	10		0.3	1.5	0.3	0.7	0.3	1.5		
	5		0.3	2[4]	0.3	0.9	0.3	2[3]		
	(5)	35	0.3	4[4]	0.3		0.3	4[3]		
		50	0.3	6[5]	0.3	2.0	0.3	6[4]		
Equatorial stratosphere	100		0.3	2[7]	0.3	1	0.3	2[8]	–100 to +20	The 26-month cycle of temperature in the middle stratosphere has been considered to be climatology, rather than climatic change
	50		0.3	2	0.3	1	0.3	2		
	10		0.3	3	0.3	1.5	0.3	3		
		35	0.3	3.5	0.3	1.5	0.3	3.5		
		50	0.3	4.5	0.3	2	0.3	4.5		

NOTE: Unless otherwise specified, values refer to temperature measurements averaged over a layer 30 to 40 m thick in the stratosphere, centred on the reporting level.

NOTES TO TABLE 2

1. The highest limit (*b*) is 7°C (over continents in winter).
2. These values relate to the systematic part of the error.
3. All values in this column are subject to substantial increase in winter.
4. Note two limits (*b*) are indicated for the same level by different series of observations. Both values may be too large because of instrumental errors in the observations on which they are based.
5. This value for 50 km compares with that given for 35 km. Again, the indicated value may well be too large. A value between 4 and 5°C is probably more realistic.
6. All values in this column relate to standard deviations of random errors. Somewhat larger errors in the low stratosphere and substantially larger errors in the high stratosphere would provide information of some value in winter. Values for limit (*b*) relating to the systematic part of the error are very variable (see paragraph 5.4.6 in WMO (1970)).
7. All values in this column are based upon apparent variability of the atmosphere as measured. Such variability includes contributions from those instrumental errors of observation which are random from sounding to sounding. These contributions may well be substantial for the instruments involved here (see paragraph 5.5.3 in WMO (1970)).
8. All values in this column relate to standard deviations of random errors. Values for the systematic part of the error are 0 for limit (*a*) (see paragraph 5.4.6 in WMO (1970)).

TABLE 3
Summary of performance limits for aerological instruments measuring humidity

Limit (*a*) — the limit of error in frost point or dew point or relative humidity below which improvement is unnecessary for the stated purpose.

Limit (*b*) — the limit of error in frost point or relative humidity or dew point beyond which the observation would have negligible value for the stated purpose.

(Associated values of relative humidity are alternative suggestions and not strict conversions)

Layer	*For local use*				*For synoptic use*				*For climatological use*				*Remarks*
	(*a*)		(*b*)		(*a*)		(*b*)		(*a*)		(*b*)		
	°C	RH (%)	°C	RH (%)	°C	RH (%)	°C	RH (%)	°C	RH (%)	°C	RH (%)	
The convective and turbulent layer near the ground	0.5	3	5	30	0.5	3	5	30	0.5	3	1.5^1	10^1	Systematic errors on a single sounding should be below 0.15°C (1% RH) if possible, so that average water content of a column of air can be specified with greater accuracy than the water content at a specific level
The troposphere above the convective layer	0.2^2 at high humidities	1^2	10	30	0.2^2	1^2	10	30	0.5	3	1.5^1	10^1	Additional requirement for measurement of very steep humidity gradients for radio meteorology
	2.5* at low humidities	10*	10	30	2.5* at low humidities	10*	10	30	0.5	3	1.5^1	10^1	

* Systematic errors on a single sounding should not exceed 1.5°C (5% RH).

NOTES TO TABLE 3

1. These values relate to the systematic parts of the error, which are constant from sounding to sounding at particular levels.
2. A direct determination of the presence of water seems more feasible.

TABLE 4
Summary of performance requirements in determining the heights of isobaric surfaces and significant points

Limit (*a*) — the limit of error beyond which improvement is unnecessary for the stated purpose.

Limit (*b*) — the limit of error beyond which the data obtained will have negligible value for the stated purpose.

(Values are standard deviations of random errors except where otherwise noted; units are geopotential metres)

Region	*Pressure level (hPa)*	*Local use*		*Synoptic use*		*Climatological use*		*Remarks*
		(*a*)	(*b*)	(*a*)	(*b*)	(*a*)	(*b*)	
Middle and high latitudes	Lower troposphere	5	45^1	1.5^4	25^5	1.5^6		Limits for isobaric surfaces in the mesosphere not assessed in detail (see paragraph 7.3.5 in WMO (1970)) Random height errors of standard deviation 85 m at each station at any level would be associated with root-mean-square wind component errors of 10 m s^{-1} at the level at middle latitudes assuming 1 000 km between stations
	300	10	80^2	1.5	70		Large^7	
	100	10	45^3	1.5	35	1.5	Even	
	50	10	30^3	1.5	10			
	30	10	30^3	1.5	20	1.5	Very	
	10		30^3	1.5	40	1.5	large	
	5		40^3	1.5	60	1.5		
	1		50^3	1.5	110	1.5		
						1.5		
Equatorial belt	Lower troposphere	5	20	1.5	12^9	1.5^6	20^{10}	
	700	5	10	1.5	12	1.5	20	
	300	10	25	1.5	12	1.5	20	
	100	10	50^8	1.5	12	1.5	20	
	10		50^8	1.5	12	1.5	20	
	1		50^8	1.5	12	1.5		
All latitudes				Height of significant levels				
				15	600			

NOTES TO TABLE 4

1. The lowest value (*b*) in low latitudes (20°) in summer is about 15 m.
2. The highest value (*b*) is 240 m (winter, North Atlantic). The lowest value (*b*) is about 25 m (low latitude 20° in summer).
3. These values are much larger in winter; of the order of 100 m at 50 hPa, increasing to 500 m at 5 hPa and 650 m at 1 hPa.
4. Values in this column probably vary with latitude from about 1.5 m at low latitudes to 3 m at high latitudes.
5. Values in this column are typical values for changes of height in 300 km in middle latitudes in a direction normal to the wind. They vary with latitude as indicated in Table XXVIII in WMO (1970). Values in the stratosphere are for conditions in summer; they increase considerably in winter, e.g. to 50 m at 50 hPa (see paragraph 7.3.5 in WMO (1970)). Limits appropriate to the standard deviation of random errors at single stations are the tabulated values divided by $\sqrt{2}$, when the standard deviations at the stations are equal.
6. Values in this column relate to systematic errors, or to the standard errors of mean values of large numbers of soundings.
7. Provided sufficiently large samples are available, limit (*b*) is controlled by factors other than the instrumental errors of observation affecting geopotential height determinations (see paragraph 7.3.6 in WMO (1970)).
8. These values vary substantially with circumstances; at different times they can be decreased, or increased, by factors of up to about 3.
9. Random errors with standard deviations of 25 m at any level have some value but degrade the effective network spacing.
10. Values in this column relate to the standard error of short-period (e.g. monthly) mean values. Corresponding values for the standard deviation of the instrumental errors which are random from sounding to sounding are $20 \sqrt{n\ m}$, where *n* is the number of observations available to form a mean.