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CHAPTER 12. MEASUREMENT OF UPPER-AIR PRESSURE, TEMPERATURE AND HUMIDITY

12.1 GENERAL

12.1.1 Definitions

The following definitions based on WMO (1992, 2015*a*) are relevant to upper-air measurements using a radiosonde:

Radiosonde: Instrument intended to be carried by a balloon 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, humidity and, often, horizontal wind, by means of a radiosonde.

Note: The radiosonde may be attached to a balloon (or another slow-moving unmanned aircraft), or the design adjusted to be dropped (as a dropsonde) from an aircraft or rocket.

Radiosonde station: A station at which observations of atmospheric pressure, temperature, humidity and usually horizontal wind 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, and so on.

This chapter deals with radiosonde systems. Measurements using special platforms, specialized equipment, and aircraft, or made indirectly by remote-sensing instruments such as microwave radiometers and Raman water vapour lidars in the boundary layer and troposphere, are discussed in other chapters of Volume III 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 Volume I, 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 hectopascals for pressure, degrees 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 (gpm), defined as 0.980 665 dynamic metres. The relationship between geopotential height and geometric height is shown in 12.3.6.2. Differences in the lower troposphere are not very large but get larger as the height increases.

The values of the physical functions and constants adopted by WMO (2011*a*) 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, relative humidity and wind are three of the basic measurements used in the initialization of the analyses of numerical weather prediction (NWP) 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 can, in practice, provide a very limited but important 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. Aircraft observations during ascent and descent are used to supplement radiosonde observations over land and in some cases may be used to replace the radiosondes at a given site. Aircraft observations at cruise level give measurements over both land and oceans. Nadir-viewing satellite observations of temperature and water vapour distribution have lower vertical resolution than radiosonde or aircraft measurements. Satellite observations have a large 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 and nowcasting. Atmospheric temperature profiles have discontinuities in the vertical, and the changes in relative humidity associated with the temperature discontinuities are usually quite pronounced (see Figure 12.1). The measurements indicate the typical structure of cloud or fog layers in the vertical. This vertical structure of temperature and water vapour 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.

High-resolution measurements of the vertical structure of temperature and relative humidity are important for environmental pollution studies (for instance, identifying the depth of the atmospheric boundary layer). This high vertical resolution is also necessary for computing the effects of atmospheric refraction on the propagation of electromagnetic radiation or sound waves. The time resolution should be as high as possible, for instance 1 s, but not more than 5 s. Besides that, information on the time and position of the radiosonde at each level is required to obtain the correct description of the atmosphere.

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Figure 12.1. Examples of temperature and relative humidity profiles in the lower and middle troposphere

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

Radiosonde observations are also important for studies of upper-air climate change. Hence, it is necessary to keep adequate records of the systems, including the software version and corrections, and consumables used for measurements, as well as the methods of observation (e.g. suspension length from the balloon) used with the systems. Climatologists would prefer that raw data be archived in addition to processed data and made available for subsequent climatological studies. It is essential to record any changes in the methods of observation introduced over time. In this context, it has proved essential 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 and complex to generate meaningful corrections at all the heights required for climate change studies. 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.

When new radiosonde designs are introduced, it is essential that enough testing be conducted of the performance of the new radiosonde relative to the old, so that time series of observations at a station can be harmonized based on comparison data. This harmonization should not result in the degradation of good measurements generated by the improved radiosonde in order to make them compatible with the poorer measurements of an earlier design. It should also be recognized that in some cases the errors in the earlier measurements were too large for use in climatological studies (this is particularly true with respect to recent relative humidity measurements, see 12.5.7).

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 hPa to 5 hPa for pressure
50 °C to −95 °C for temperature
100 % to 1 % for relative humidity
30 hPa at the surface to 10^{-4} hPa at the tropopause for water vapour pressure in the tropics

Systems also need to be able to sustain continuous reliable operation when operating in heavy rain, in the vicinity of thunderstorms, and in severe icing conditions.

The coldest temperatures are most often encountered near the tropical and subtropical tropopause, although in winter very cold temperatures can also be observed at higher levels in the stratospheric polar vortex. Figure 12.2 shows examples of profiles from the subtropics: example (a) in Yangjiang, China (22º N) in summer, and example (b) at 50º N in summer and winter in the United Kingdom. The colder temperatures near the tropopause in the tropics pose a major challenge for operational relative humidity sensors, because few currently respond very rapidly at temperatures below −70 °C (see 12.5.7.6 and 12.5.7.7). Thus, radiosondes that can perform well throughout the troposphere at mid-latitudes may have less reliable relative humidity measurements in the upper troposphere in the tropics.

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Figure 12.2. Examples of complete individual temperature profiles made with large balloons suitable for climate observations

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A radiosonde measurement is close to an instant sample of a given layer of the atmosphere (a radiosonde usually ascends 300 m in 1 min). When short-term fluctuations in atmospheric temperature from gravity waves and turbulence are small, the radiosonde measurement can represent the situation above a location very effectively for many hours. On the other hand, when the atmosphere is very variable (for example, a convective atmospheric boundary layer), the instant sample may not be valid for longer than a minute and may not represent a good average value above the location, even for an hour. In Figure 12.2(a), radiosonde temperatures in the troposphere were more reproducible with time than in the stratosphere because of the larger influence of gravity waves in the stratosphere. These larger differences at upper levels were not the result of instrument error. Similarly, the variation of temperatures in the vertical in the stratosphere in Figure 12.2(b) was not the result of instrument error, as the same structure was measured by two different radiosonde types on the test flights.

12.1.3.2 Relationships between satellite and radiosonde upper-air measurements

Nadir-viewing 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 emissions in the infrared, or alternatively oxygen or water vapour emissions at microwave frequencies (see Volume IV, Chapter 3). Both infrared and microwave sounding measurements are essential for current operational numerical weather prediction. The radiance observed by a satellite channel is composed of atmospheric emissions 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 a single satellite temperature channel approximate the mean layer temperature of a layer at least 10 km thick. However, much finer vertical resolution has been achieved by the recent Fourier-transform interferometers operating in the infrared, using information from a much larger number of channels with slightly different absorption characteristics. 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 more difficult to specify at any given location.

Most radiances observed by nadir-viewing 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 heavily 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. Therefore, water vapour distribution in the vertical can be derived only once suitable measurements of vertical temperature structure are available.

Limb-viewing satellite systems can provide measurements of atmospheric structure with higher vertical resolution than nadir-viewing systems; an example of this type of system is temperature and water vapour measurement derived from global positioning system (GPS) radio occultation. In this technique, vertical structure is measured along paths in the horizontal of at least 200 km (Kursinski et al., 1997). The technique is now in widespread use as it provides improved measurements of vertical temperature structure, particularly around the tropopause where radiosondes are not 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, or from the numerical weather prediction model fields themselves. The radiosonde 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, together with aircraft, are complementary observing systems and provide a more reliable global observation system when used together. Radiosonde and aircraft observations improve numerical weather prediction, even given the much larger volume of satellite measurements available.

12.1.3.3 Maximum height of radiosonde observations

Radiosonde observations are used regularly for measurements up to heights of about 35 km (see, for example, Figure 12.2). 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 tend to increase with height, but the rate of increase with modern radiosondes is not that high and useful measurements can be made up to 35 km, particularly at night.

When planning radiosonde measurements for climate monitoring, it is necessary to ensure that a sufficient number of large balloons are procured to obtain measurements up to 30 km on a regular basis in each region.

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

12.1.4 Accuracy requirements

This section summarizes the requirements for uncertainty (always stated in terms of k = 2, see Volume I, Chapter 1) of the meteorological variables measured by radiosondes and compares them with typical operational performance. A more detailed discussion of performance and sources of errors is given in detail in the later sections dealing with the individual meteorological variable (see 12.3.5, 12.3.7, 12.4.7 and 12.5.7 for pressure, height, temperature and relative humidity, respectively). The definition of uncertainty, systematic bias and so on can be found in Volume I, Chapter 1.

Estimates of achievable optimum uncertainty for radiosonde observations, as of 2012, are included in Annex 12.A. This annex was generated following the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*). It describes the optimum performance that can currently be obtained from operational radiosondes.

A summary of requirements for uncertainty and vertical resolution limits for radiosonde observations extracted from WMO documents is presented in Annex 12.B. These tables include information from the WMO observing requirements database (OSCAR/Requirements; see WMO, 2014), the observation requirement targets published by WMO (2009) for the Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN), and limited information from atmospheric variability studies in WMO (1970).

The WMO observing requirements database includes three limits for most meteorological variables:

(a) The goal: an ideal requirement;

(b) The threshold: the minimum requirement to be met to ensure that data are useful;

(c) A breakthrough: an intermediate level between threshold and goal which, if achieved, would result in a significant improvement for the target application.

Tables 12.B.1, 12.B.2 and 12.B.3 in Annex 12.B are based mainly on the requirements of the high-resolution numerical weather prediction application area, although information on goals derived from atmospheric variability studies are also shown when the goals differ from those established in the WMO observing requirements database. Climate requirements are based on the GRUAN requirements and those in the section of the observing requirements database for Atmospheric Observation Panel of GCOS (AOPC) or Stratospheric Processes and their Role in Climate (SPARC) activities. Again, when there are significant differences between the goals from the two databases, these are indicated in the tables. Requirements for geopotential height in Table 12.B.4 were derived as described in Annex 12.B.

A radiosonde meeting the less stringent breakthrough requirements, as summarized in Annex 12.A, should provide measurements that give good value for money in terms of national targeted use. However, the less stringent accuracy requirements will not meet the expectations of some users, for instance for primary sites used to detect climate change. Thus, an operational decision has to be made as to the quality of the observation required by the national network, taking into account that the use of such data in forecasts will improve forecast quality across the country if the observation meets the breakthrough targets.

The requirements for spacing between observations in the horizontal from the WMO observing requirements database have not been shown here, but these clearly show that radiosonde observations on their own cannot meet the minimum requirements of the WMO Integrated Global

Observing System (WIGOS), and must be supplemented by temperature, relative humidity and wind measurements from other observing systems.

12.1.4.1 Geopotential height: requirements and performance

Modern radiosonde systems can have systematic pressure bias a little larger than 1 hPa near the surface, but systematic errors as large as this at pressures lower than 100 hPa are now rare (see Table 12.4). The radiosondes still using the best pressure sensors can measure heights near 10 hPa with a random error (k = 2) between 300 and 400 m, that is, with a random error in pressure of about 0.6 hPa.

Thus, the uncertainty goal for height measurements for numerical weather prediction can be met by most radiosondes using a pressure sensor up to 100 hPa. However, it requires a radiosonde measuring height with GPS technology to measure up to 30 km with a random error of only 20 m, which is equivalent to a random error less than or equal to 0.05 hPa in pressure, depending on the uncertainty of the radiosonde temperature measurements.

The uncertainty goal for cloud-base heights in the lower troposphere in Table 12.B.4 of Annex 12.B requires pressure uncertainties (k = 2) of only 3 hPa associated with the cloud-base height. Most modern radiosondes can come close to this requirement.

Ozone concentrations in the stratosphere have pronounced gradients in the vertical, and height assignment errors from even relatively small pressure sensor errors introduce significant inaccuracies into the ozonesonde profile reports at all latitudes. This has proved to be one of the limiting factors in these measurements when using the older type of radiosonde with larger pressure errors in the stratosphere.

12.1.4.2 Temperature: requirements and performance

Most modern radiosonde systems (introduced since 2000) measure temperature in the troposphere and stratosphere up to a height of about 31 km with an uncertainty (k = 2) between 0.4 and 1 K. This is usually close to the optimum performance for numerical weather prediction suggested in Table 12.B.2 of Annex 12.B. However, uncertainty well in excess of 2 K can still be found in some national radiosonde networks in tropical regions. If used, measurements with such large errors damage numerical weather prediction forecasts.

In the stratosphere, radiosonde temperature uncertainties can be close to the goal for numerical weather prediction, but require some improvement in daytime conditions to be optimized for climate requirements.

As the goals for climate temperatures are more demanding than for numerical weather prediction, the GRUAN Lead Centre continues to work with manufacturers and operators to reduce the uncertainty of the current operational measurements in the troposphere and stratosphere. In this case, it is extremely important that systematic bias be as near constant with time as possible, requiring tighter limits on the methods of observation than at standard operational sites. To obtain the most useful performance, operators must take care to prepare and operate the radiosondes according to the instructions, whether from this Guide, the manufacturer or at GRUAN stations, according to the procedures agreed with the GRUAN Lead Centre. In the case of GRUAN, the details of the radiosonde preparation must be noted and archived as part of the metadata associated with the measurement (Immler et al., 2010).

12.1.4.3 Relative humidity: requirements and performance

The uncertainties in modern relative humidity sensor measurements at temperatures higher than –50 °C fall mostly within the range of 5 % to 14 % relative humidity (RH). Thus, the measurements mostly meet the breakthrough limit for numerical weather prediction, but many need improvement to meet the breakthrough limit for climate measurements (see Annex 12.B, Table 12.B.3).

At temperatures lower than −50 °C, the uncertainties increase, with the best operational radiosonde sensors having an uncertainty of about 16 % relative humidity at −70 °C, i.e. close to the breakthrough for numerical weather prediction and not meeting the breakthrough for climate requirements. However, most modern sensors have uncertainties of about 24 % relative humidity at the lowest temperatures. Several problems were identified in the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*). It is expected that the uncertainties in upper troposphere relative humidity will improve with time as these are rectified.

12.1.5 Methods of measurement

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

12.1.5.1 Constraints on radiosonde design

Certain compromises are necessary when designing a radiosonde:

(a) 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 and heat exchange in the infrared. The radiation corrections work most reliably if the temperature sensor and its supports are designed so that the solar heating does not vary significantly as the radiosonde rotates in flight relative to the sun. Software corrections for the residual solar heating are then applied during data processing.

(b) 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 is usually more important than perfect exposure to the ambient air. Thus, protective covers or ducts are used mostly with a relative humidity sensor. One of the alternatives is to have two sensors which alternate: one is heated to drive off contamination while the other reports the relative humidity; then the second sensor is heated while the first reports the relative humidity, and so on. Humidity sensors are often placed close to the temperature sensor since, until recent years, the humidity sensor was assumed to be at the same temperature as the temperature sensor. However, many radiosondes now measure the temperature of the humidity sensor directly, as the humidity sensor’s temperature is rarely exactly the same as the air temperature reported by the radiosonde. If this is done, the relative humidity sensor may be given an improved exposure away from contamination from the main temperature sensor and its supports.

(c) 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.

(d) In many modern radiosondes a pressure sensor is not used, and geometric height is measured using GPS technology and then converted into geopotential height based on knowledge of the gravitational fields at the location.

Other important features required in radiosonde design are reliability, robustness, and light weight and small dimensions to facilitate the launch. 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 about once per second, corresponding to a minimum sample separation of about 5 m in the vertical. Since radiosondes are generally used only once, or not more than a few times, they 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. Many of the most important GCOS stations, for example, in Antarctica, are on sites where radiosondes cannot be delivered more than once per year.

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 battery variations without a loss of measurement accuracy or an unacceptable drift in the transmitted radio frequency.

12.1.5.2 Radio frequency used by radiosondes

The radio frequency spectrum bands currently used for most radiosonde transmissions are shown in Table 12.1. These correspond to the meteorological aids allocations specified by the International Telecommunication Union (ITU) Radiocommunication Sector radio regulations.

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Table 12.1. Primary frequencies used by radiosondes in the meteorological aids bands

TABLE: Table horizontal lines

Radio frequency band (MHz)	*Status*	*ITU Regions*
400.15 – 406	Primary	All
1 668.4 – 1 700	Primary	All

Note: Some secondary radar systems manufactured and deployed in the Russian Federation may still operate in a radio frequency band centred at 1 780 MHz.

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The radio frequency 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, be usually determined by the method of upper-wind measurement used (see Volume, Chapter 13). The frequency band of 400 MHz is usually used when navigational aid windfinding is chosen, and 1 680 MHz when radiotheodolites or a tracking antenna are to be used with the radiosonde system.

The radio frequencies listed in Table 12.1 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 radio frequency drift and bandwidth occupied by an individual flight.

Any organization proposing to fly radiosondes should check that suitable radio frequencies 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 requirements from governments to improve the efficiency of radio frequency 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 will become impracticable in many countries. 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 will have to be better than ±5 kHz in countries with dense radiosonde networks, and not worse than about ±200 kHz in most of the remaining countries.

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

12.1.6 Radiosonde errors: general considerations

12.1.6.1 Types of error

This section contains a detailed discussion of the errors encountered with radiosonde sensors.

Measurement errors 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.

However, for many users it is also helpful to take note of the magnitude of the representativeness errors that are associated with a measurement (see Kitchen, 1989, and Volume I, Chapter 1). For instance, radiosonde temperature observations are assigned an error in data assimilation schemes, and this has more to do with a representativeness error than the small instrumentation errors identified in 12.4.7. These errors differ depending on the atmospheric situation and also on the use made of the measurement. For example, as the scales of motion represented in a numerical weather prediction model increase, the radiosonde representativeness errors ought to decrease because the model represents more of what the radiosonde measures. On the other hand, a climatologist wants measurements that are close to a longer-term average, representing a significant area around the launch site. The structure introduced by localized small-scale fluctuations in the radiosonde measurement is undesirable for this purpose.

12.1.6.2 Potential references

High-precision tracking radar measurements or GPS height measurements can allow systematic errors in geopotential height measurements to be quantified. 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 newly developed radiosondes measure temperatures at night which fall within a range of ±0.2 K at a height of 30 km (WMO, 2006*a*, 2011*b*). Thus, at night, it is possible to identify systematic errors that bias radiosonde measurements away from this consensus.

However, interpreting daytime temperature comparisons with similar uncertainty is still not feasible. For instance, average temperatures in the same tests fall within about ±0.5 K at a height of 30 km. When used in big international tests, the scientific sounding instrumentation has not yet achieved the required performance in daytime to be able to identify correct measurements with the same uncertainty as at night.

Relative humidity measurements can be checked at high humidity when the radiosondes pass through clouds. Here, laser ceilometer and cloud radars can provide better evidence on the cloud observed by the radiosonde during its ascent. The vertical structure in relative humidity reported by radiosondes, including the presence of very dry layers, can be validated by comparison 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 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 comparisons (WMO, 1987, 1991, 1996*a*, 2006*b*) and the tests performed in Brazil (WMO, 2006*c*), Mauritius (WMO, 2006*a*) and Yangjiang, China (WMO, 2011*b*). Results from these and other tests using the same standards in the United Kingdom (see results from the Camborne Met Office (WMO, 2010)), the United States and Switzerland will sometimes be quoted in the subsequent sections.

There are several national facilities in which the performance of radiosonde sensors can be tested at different pressures and temperatures in the laboratory. The WMO Radiosonde Humidity Sensor Intercomparison (WMO, 2006*b*) contains results from laboratory comparisons with humidity standards in the Russian Federation. These results can be helpful in identifying some, but not all, of the problems identified when flying in the atmosphere.

12.1.6.3 Sources of additional error during radiosonde operations

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, providing 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 specifications 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 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 procedure necessary to deal with a special situation or combination of events normally dealt with instinctively by an expert human operator.

12.2 RADIOSONDE ELECTRONICS

12.2.1 General features

A basic radiosonde design usually comprises three main parts as follows:

(a) The sensors plus references;

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

(c) The radio transmitter.

In rawinsonde systems (see Volume I, Chapter 13), there are also 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 one measurement cycle lasting typically 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

Radiosonde batteries should be of sufficient capacity to power the radiosonde for the required flight time in all atmospheric conditions. For radiosonde ascents to 5 hPa, radiosonde batteries should be of sufficient capacity to supply the required currents for up to three hours, given that the radiosonde launch may often be delayed and that flight times may be as long as two hours. Three hours of operation would be required if descent data from the radiosonde were to be used. Batteries should be as light as practicable and should have a long storage life. They should also be environmentally safe following use. Many modern radiosondes can tolerate significant changes in output voltage during flight. Two types of batteries are in common use, the dry-cell type and water-activated batteries.

The use of dry-cell batteries has increased rapidly as these have the advantages of being widely available at very low cost because of the high volume of production worldwide and of posing less risk in terms of occupational health and safety (and environmental impact). However, they may have the disadvantage of having limited shelf life. Also, their output voltage may vary more during discharge than that of water-activated batteries.

Water-activated batteries usually use a cuprous chloride and sulphur mixture. The batteries can be stored for long periods. The chemical reactions in water-activated batteries generate 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.

Care must be taken to ensure that batteries do not constitute an environmental hazard once the radiosonde falls to the ground after the balloon has burst. See 12.7.5 and Annex 12.C for a more detailed discussion on environmental issues.

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. Modern transmitter designs are usually 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 are important. At 400 MHz, widely used radiosonde types are expected to have a transmitter power output lower than 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 with radiosonde type. It would be preferable in the future if radiosonde manufacturers could agree on a standard method and format for transmission of data from the radiosonde to the ground station, which would allow user interoperability between radiosonde types without the need to modify the ground reception hardware and software each time. In any case, the radiocommunication authorities in many regions of the world will require that radiosonde transmitters meet certain specifications in the future, so that the occupation of the radio-frequency spectrum is minimized and other users can share the nominated meteorological aids radio-frequency bands (see 12.1.5.2).

12.3 PRESSURE SENSORS (INCLUDING HEIGHT MEASUREMENTS)

12.3.1 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 over most of the range and a resolution of 0.01 hPa for pressures less than 100 hPa. 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 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.

Historically, when reliable pressure sensors for low pressure were being manufactured, sensors with poor performance were replaced by pressure measurements deduced from radar heights, as in the United Kingdom before 1978. In some countries of the Commonwealth of Independent States, very accurate secondary radars are used to measure geometric heights instead of using a pressure sensor on the radiosonde.

Today, many modern radiosonde systems use GPS navigation signals to locate the position of the radiosonde and have dispensed with the use of a pressure sensor on the radiosonde (to save on consumable costs). As a result, geometric height, and hence geopotential height, is measured directly (see 12.3.6), with the pressure changes in flight computed from the radiosonde temperature and humidity measurements.

12.3.2 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 were 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 12.3.3).

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.

12.3.3 Aneroid capsule (capacitive)

Many modern radiosonde designs use aneroid capsules of smaller diameter (30 mm or less in diameter) 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:

$$C = \in \cdot S / e \qquad (12.1)$$

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:

$$- \in \cdot S / e^2 \cdot de / dp \qquad (12.2)$$

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 electronic oscillator with associated reference capacitors. This arrangement needs to measure very small variations of capacity (for example, 0.1% 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 which has 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.

12.3.4 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 silicon cover.

A 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 and is now in widespread use. Because the sensor is very small, it is possible to avoid the calibration errors of the larger capacitive aneroid sensors introduced by changes in temperature gradients across the aneroid sensor and associated electronics during an ascent.

12.3.5 Pressure sensor errors

Systematic errors and the radiosonde error (flight-to-flight variation at k = 2) have been estimated from the WMO international radiosonde comparisons for selected radiosonde types. The results are shown in Table 12.2. The range of values of systematic error usually represents the spread of results from several tests.

Aneroid capsules were liable to change calibration unless they had 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, went some way toward reducing these errors. Nevertheless, corrections based on ground checks relied on a fixed error correction pattern across the working range. In practice, the change in pressure sensor calibration was more variable over the working range.

The MRZ secondary radar system was introduced into the Russian Federation in the mid-1980s, with the results shown obtained in 1989. There is no pressure sensor in this system. The pressure is computed from measurements of geometric height which are then converted to geopotential height as shown in 12.3.6. The quality of the measurements depended on the performance of each individual secondary radar.

The VIZ MKII and Meisei RS2-91 radiosondes had capacitive aneroid sensors, but of differing design. Overall uncertainties (k = 2) for the capacitive aneroids were usually lower than 2 hPa at most pressures. However, these capacitive aneroid capsules could have significant systematic errors, particularly when the internal temperature of the radiosonde changed and temperature gradients developed across the sensor and its associated electronics. Systematic errors with capacitive aneroids were usually not larger than ±1 hPa. However, errors could be larger if the pressure sensors experienced very large thermal shock during the launch.

The Vaisala RS92 uses a silicon sensor. The performance of these sensors did not show the effects of thermal shock, and the uncertainties obtained with the systems were even better than with the capacitative aneroids.

The consequences of the pressure errors in Table 12.2 on reported temperatures would be as follows: 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 1 K for most situations at 10 hPa.

12.3.5.1 Relationship of geopotential height errors to pressure errors

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

$$\varepsilon_z(t_1) = \frac{R}{g}\int_{p_0}^{p_1}\left[\varepsilon_T(p) - \frac{\delta T}{\delta p}\varepsilon_p(p)\right]\frac{dp}{p} + \frac{R}{g}\int_{p_1}^{p_1+\varepsilon_p(p_1)}\left[T_v(p) + \varepsilon_T(p) - \frac{\delta T}{\delta p}\varepsilon_p(p)\right]\frac{dp}{p} \qquad (12.3)$$

where p_0 is the surface pressure; p_1 is the true pressure at time t_1; $p_1 + \varepsilon_p(p_1)$ is the actual pressure indicated by the radiosonde at time t_1; $\varepsilon_T(p)$ and $\varepsilon_p(p)$ 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 (2011*a*).

Table 12.2. Range of systematic error and radiosonde error (flight to flight, k = 2) and overall uncertainty in pressure from the WMO international radiosonde comparisons and associated tests

TABLE: Table horizontal lines

Radiosonde type	*Systematic error*			*Sonde error*			*Uncertainty*		
Pressure level (hPa)	*850*	*100*	*10*	*850*	*100*	*10*	*850*	*100*	*10*
MRZ[a] (Russian Federation)	−1.5 to −0.5	−1.2 to −0.8	0 – 0.2	7	3.5	0.5	8	4	0.7
Meisei RS2-91	0.2 – 1	−0.1 – 0.5	−0.2 – 0.2	1	0.6	0.6	2	1.1	0.8
VIZ MKII	0 – 1	0.7 – 1.1	0.3 – 0.7	1.6	0.6	0.4	2.5	1.6	1
Vaisala RS92, silicon sensor	< 0.5	< 0.3	< 0.2	0.8	0.4	0.2	1	0.6	0.4
MODEM M2K2[a]	−0.8 to −0.4	< 0.1	< 0.05	1.2	0.4	0.03	1.6	0.4	0.05
Vaisala RS92[a]	< 0.5	< 0.1	< 0.05	1.2	0.4	0.03	1.6	0.4	0.05
Lockheed Martin Sippican (LMS),[a] LMG-6	< 0.5	< 0.1	< 0.05	1.2	0.4	0.03	1.2	0.4	0.05

Note:

a Does not use a pressure sensor but computes pressure from geopotential height measurements; see 12.3.6.

ELEMENT 6: Floating object (Automatic)

Table 12.3. Systematic errors in geopotential height (gpm) from given pressure and temperature errors

TABLE: Table horizontal lines

	ε_T,T *error (K)*	ε_p, P *error (hPa)*	*Latitude*	*300 hPa*	*100 hPa*	*30 hPa*	*10 hPa*
Standard pressure height, T error	0.25	0	All	9	17	26	34

Standard pressure height, p error	0	−1	25º N	3	12	−2	−24
Standard pressure height, p error	0	−1	50º N summer	3	5	1	−20
Standard pressure height, p error	0	−1	50º N winter	3	5	6	−4
Significant level height, p error	0	−1	25º N	27	72	211	650
Significant level height, p error	0	−1	50º N summer	26	72	223	680
Significant level height, p error	0	−1	50º N winter	26	70	213	625

END ELEMENT

For a specified standard pressure level, p_s, the second term in equation 12.3 disappears because there is no error in p_s, and so the error in the standard pressure level geopotential height is smaller:

$$\varepsilon_z(p_s) = \frac{R}{g}\int_{p_0}^{p_s}\left[\varepsilon_T(p) - \frac{\delta T}{\delta p}\varepsilon_p(p)\right]\frac{dp}{p} \tag{12.4}$$

And for radiosondes without a pressure sensor using a radar:

$$\varepsilon_z(p_s) = T_v(p_s)\int_{z_0}^{z_{ps}} g/T^2\left[\varepsilon_T(z) + \varepsilon_z(Range,\theta)\cdot dT_v/dz\right] \tag{12.5}$$

where Z_{ps} is the geopotential height of the specified pressure level p_s, and the error in geopotential height for a radar is a function of slant range and elevation angle (θ), and will vary from flight to flight according to the wind conditions.

Table 12.3 shows the errors in geopotential height that are caused by radiosonde sensor errors for typical atmospheres. The geopotentials of given pressure levels have small errors, whether caused by a radiosonde temperature or pressure error. The pressure error has a slightly different effect at different latitudes because the typical temperature profile structure varies with latitude. However, the same pressure sensor errors produce much larger errors at the heights of specific structures, such as temperature inversions, including at the tropopause, and cloud tops and bases.

The importance of equations 12.4 and 12.5 is that the errors in standard pressure level geopotentials are primarily related to the temperature errors, and so if geopotential heights are compared against collocated NWP first-guess forecast fields, the height anomalies give an indication of the relative temperature performance at the two sites (see WMO, 2003).

12.3.6 Use of geometric height observations instead of pressure sensor observations

12.3.6.1 General

Geometric height observations can now be provided by GPS radiosondes that decode global positioning satellite signals, as opposed to the early GPS radiosondes that did not decode the signals. The geometric height observations have small enough uncertainty (between 10 and 20 m) to be used to compute pressure at a given time into flight, using surface pressure and temperature and relative humidity observations (see equations 12.12 and 12.13). In the stratosphere, the computed pressures are found to have smaller uncertainty than measurements provided by the best radiosonde pressure sensors (see Table 12.2).

The elimination of the pressure sensor from GPS radiosondes provides a considerable saving in terms of the cost of some radiosondes, but it is also necessary to check user requirements for the non-hydrostatic numerical weather prediction models that are being introduced, since direct measurements of pressure and geopotential height in the troposphere may be of some advantage when hydrostatic balance does not represent atmospheric conditions.

12.3.6.2 Method of calculation

The conversion from geometric height measured with a GPS radiosonde to geopotential height is purely a function of the gravitational field at a given location and does not depend on the temperature and humidity profile at the location. The gravitational potential energy (Φ_1) of a unit mass of anything is the integral of the normal gravity from mean sea level (z = 0) to the height of the radiosonde ($z = z_1$), as given by equation 12.6:

$$\Phi_1 = \int_0^{z_1} \gamma(z,\varphi) \cdot dz \qquad (12.6)$$

where $\gamma(z, \varphi)$ is the normal gravity above the geoid. This is a function of geometric altitude, z, and the geodetic latitude φ.

This geopotential is divided by the normal gravity at 45º latitude to give the geopotential height used by WMO, as:

$$Z_1 = \Phi_1 / \gamma_{45°} \qquad (12.7)$$

where $\gamma_{45°}$ was taken in the definition as 9.806 65 m s^{-2}. Note that surface gravity is greatest at the poles (9.832 18 m s^{-2}) and least at the Equator (9.780 33 m s^{-2}).

The variation of gravity with height must take into account the ellipsoidal shape of the Earth and the Earth’s rotation. However, when the variation of γ with height was taken into account, the geopotential height, Z_1, at geometric height, z_1, was approximated using the Smithsonian meteorological tables (List, 1968) as:

$$Z_1(z_1,\varphi) = \left(\gamma_{SMT}(\varphi)/\gamma_{45°}\right) \cdot \left(\left(R_{SMT}(\varphi) \cdot z_1\right) / \left(R_{SMT}(\varphi) + z_1\right)\right) \qquad (12.8)$$

where $R_{SMT}(\varphi)$ is an effective radius of the Earth for latitude (φ) and is the value in the Smithsonian tables which was chosen to take account of the actual changes with geometric height in the combined gravitational and centrifugal forces. It is not the actual radius of the Earth at the given latitude. This is shown in Figure 12.3, where the Smithsonian radius increases from the Equator to high latitudes, but the actual radius of the Earth’s ellipsoid is largest at the Equator and smallest at the poles.

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Figure 12.3. Variation of the Earth’s radius with latitude compared to the variation of the Smithsonian table radius used in equation 12.8

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As the values for $R_{\mathrm{SMT}}(\varphi)$ in the Smithsonian tables were obtained around 1949, the International Ellipsoid 1935 was used in the computations rather than the World Geodetic System 1984 (WGS-84) currently used with GPS receivers. Also, the Smithsonian tables used a value for $\gamma_{\mathrm{SMT}}(\varphi)$ of:

$$\gamma_{\mathrm{SMT}}(\varphi) = 9.806\,16 \cdot \left(1 - 0.002\,637\,3 \cdot \cos(2\varphi) + 0.000\,005\,9 \cdot \cos(2\varphi)^2\right)\left[\mathrm{m\ s^{-2}}\right] \qquad (12.9)$$

This formula was not explicitly derived in the published scientific literature, although it was recommended for meteorological use by the International Association of Geodesy in 1949.

An alternative expression for the relationship in equation 12.8 has been proposed by Mahoney (personal communication), based on the WGS-84 geoid. Then, geopotential height for geometric height, z_1, becomes:

$$Z_1(z_1,\varphi) = \left(\gamma_{\mathrm{s}}(\varphi)/\gamma_{45°}\right) \cdot \left(\left(R(\varphi) \cdot z_1\right)/\left(R(\varphi) + z_1\right)\right) \qquad (12.10)$$

where $\gamma_{\mathrm{s}}(\varphi)$ is the normal gravity on the surface of an ellipsoid of revolution, and where:

$$\gamma_{\mathrm{s}}(\varphi) = 9.780\,325 \cdot \left(\left(1 + 0.001\,931\,85 \cdot \sin(\varphi)^2\right) \Big/ \left(1 - 0.006\,694\,35 \cdot \sin(\varphi)^2\right)^{0.5}\right) \qquad (12.11)$$

with the radius $R(\varphi)$ = 6 378.137/(1.006 803 – 0.006 706 · sin(φ)^2), giving results for R similar to the values in the Smithsonian tables.

If the geopotential height for a geometric height of 30 km is computed, it ranges from 29.778 5 km at the Equator to 29.932 km at 80° N, whether equations 12.8 and 12.9 or 12.10 and 12.11 are used. Differences between the geopotential height values obtained by the two methods are less than 1 m, and as such are not critical for meteorologists.

The difference between geometric height and geopotential height increases with height above the Earth's surface. An example of typical differences taken from measurements in the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China, at 22° N is shown in Table 12.4.

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Table 12.4. Differences between geopotential and geometric height measured at the WMO Radiosonde Intercomparison in Yangjiang, China, at 22° N

TABLE: Table horizontal lines

Geopotential height	*Geopotential – geometric height*
8 000	25
16 000	70
24 000	135
32 000	220

END ELEMENT

Once the variation of the geopotential heights with respect to temperature and relative humidity has been established, the pressures can be computed integrating upwards from the measured surface pressure, using the hypsometric relationship, in a discrete form:

$$L_n\left(p_{i+1}/p_i\right) = -9.806\,65 \cdot dZ/R^* \cdot T_{\mathrm{v}} \qquad (12.12)$$

where p is the pressure in hPa; R^* is the gas constant for dry air; T_{v} is the mean virtual temperature for the layer in degrees K; dZ is the layer thickness in geopotential height; and i refers to the lower boundary of this layer.

The virtual temperature T_{v} is computed from:

$$T_{\mathrm{v}} = T\Big/\Big(1-\left(U/100\right)\cdot\left(e_s\left(T\right)/p\right)\cdot\left(1-\varepsilon_a\right)\Big) \qquad (12.13)$$

where U is the relative humidity of the air, e_s is the saturation vapour pressure for water vapour and ε_a the ratio of the molecular weight of wet and dry air, with ε_a = 0.622.

It has to be emphasized again that the radiosonde temperature and relative humidity are used only in the computation of the pressures with systems using GPS geometric height measurements, as the geopotential values come purely from the geometric heights and the Earth's gravitational fields.

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 the Russian Federation 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 better pressure accuracy might require height corrections for the conditions encountered in individual flights.

12.3.7 Sources of error in direct height measurements

12.3.7.1 In GPS geometric height measurements

As long as there is no local interference at GPS navigation signal frequencies, most modern radiosonde systems are able to generate heights with good accuracy relative to the height where GPS lock occurs in flight. However, the software has to be able to interpolate reliably back to the surface (taking into account changes in the balloon rate of ascent just after launch) in order to ensure best performance in GPS measurements. In the WMO Intercomparison of High Quality Radiosondes in Yangjiang, China (WMO, 2011*b*), some of these interpolation software modules worked better than others, and systematic errors larger than 10 m resulted in the worst cases, persisting throughout the flight of a given radiosonde type.

It is essential to check the height of the local GPS antenna relative to the surface pressure sensor and ensure that this is used correctly in the radiosonde system software computations. Remember that a mismatch (or pressure error) of 1 hPa in the pressure at the antenna relative to the surface pressure sensor at the radiosonde station will result in a 10 m height bias throughout the flight.

In-flight processing must be able to cope with significant variations (positive and negative) in the rates of ascent of the balloons lifting the radiosonde. Errors in temperature and relative humidity will only affect the pressure computation from the geopotential heights (see equations 12.12 and 12.13). The effect of temperature errors on pressure computations can be judged from the values of height errors in Table 12.3 resulting from a 0.25 K temperature error throughout the profile. This temperature error would lead to pressure errors of 0.4, 0.3, 0.13 and 0.05 hPa at nominal pressures of 300, 100, 30 and 10 hPa, respectively.

Thus, in the stratosphere, GPS geometric heights are able to deliver much more reliable height measurements than any other operational height measuring system. Near the surface, GPS height measurements must be performed with care to be of similar quality to the best pressure sensors. The breakthrough requirements for pressure in Annex 12.A can be achieved with GPS radiosondes at all pressures. However, it is not obvious that all GPS radiosonde systems can achieve the optimum pressure sensor requirements at low levels, while at pressures lower than 100 hPa, optimum requirements could be achieved as long as temperature errors are low.

12.3.7.2 In radar height measurements

The effect of radar observational errors upon windfinding is considered in Volume I, Chapter 13. However, for radar heights (random and systematic) errors in elevation 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 as follows:

(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 state 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 the following:

(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 routine station maintenance. These systems are not suitable for use in countries where technical support facilities are limited.

12.4 TEMPERATURE SENSORS

12.4.1 General requirements

The best modern temperature sensors have a speed of response to changes of temperature which is fast enough to ensure that systematic bias from thermal lag during an ascent, the typical rate of ascent being 5 to 6 m s^{-1}, remains less than 0.1 K through any layer of depth of 1 km in the troposphere and less than 0.2 K through any layer of similar depth in the stratosphere. This is achieved in most locations using a sensor with a 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. There must be as small a variation as possible in the area of cross-section for solar heating as the sensor rotates relative to the sun during ascent. Heat exchange in the infrared needs to be avoided by using sensor coatings that have low emissivity in the infrared.

Temperature sensors also need to be sufficiently robust to withstand buffeting during launch and sufficiently stable to retain accurate calibration over several years. The main types of temperature sensors in routine use are resistive sensors (for example, thermistors made of ceramic resistive semiconductors or metal resistors), capacitive sensors and thermocouples.

The rate of response of the sensor is usually measured in terms of the time constant of response, τ. This is defined (as in Volume I, Chapter 1, 1.6.3) by:

$$dT_e/dt = -1/\tau \cdot (T_e - T) \tag{12.14}$$

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 % 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/diffusion 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 a fast response. The variation of the time constant of response with the mass rate of airflow can be expressed as:

$$\tau = \tau_0 \cdot (\rho \cdot v)^{-n} \tag{12.15}$$

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

The value of n varies between 0.4 and 0.8, depending on the shape of the sensor and on the nature of the airflow (laminar or turbulent). A selection of the time constants of response of both older and modern types of temperature sensors is shown in Table 12.5. These are for pressures of 1 000, 100 and 10 hPa, with a rate of ascent of 5 m s^{-1}. The values were derived from a combination of laboratory testing and comparisons with very fast response sensors during ascent in radiosonde comparison tests.

Modern bead thermistors, wire thermocapacitors and thermocouples have a very fast response, so the systematic errors from thermal lag are expected to be less than 0.05 K in the upper troposphere for the better sensors, and less than 0.1 K in the upper stratosphere.

WMO (2011*b*) shows examples in which the response speeds of most of the bead thermistors used by radiosondes in the test were similar or slightly faster than those of the chip thermistor included in Table 12.5.

ELEMENT 10: Floating object (Automatic)

Table 12.5. Typical time-constants of response of radiosonde temperature sensors

TABLE: Table horizontal lines

Temperature sensor	*Operational use*	*τ (1 000 hPa)*	*τ (100 hPa)*	*τ (10 hPa)*
Chip thermistor,[a] 0.4 x 0.8 x 0.8 mm	2003–	≤ 1	≤ 3	≤ 10
Wire thermocapacitor,[a] diameter 0.1 mm	2002–	0.4	1.1	3

Copper-constantan thermocouple,[a] diameter 0.06 mm	1991–	< 0.3	< 0.8	2
Other modern bead thermistors[a]	2005–	≤ 1	≤ 4	5 – 12

Note:

a The time constants of response at 10 hPa of the chip thermistors in Yangjiang, China, were larger than those of the Copper-constantan thermocouple by about 4 s. The other small bead thermistors had time constants of response between 3 and 10 s larger than the Copper-constantan thermocouple. The wire thermocapacitor showed time constants of response of at least 4 s, a little larger than the results from the laboratory test cited above. This may be because the diameter of the wire thermocapacitor in the Vaisala RS92 radiosondes had been increased in 2007 by incorporating a quartz support fibre, and may also be a consequence of the software used with the sensor in Yangjiang.

END ELEMENT

12.4.2 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:

$$R = A \cdot \exp\left(B/T\right) \tag{12.16}$$

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 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. Solar heating of a modern chip thermistor is about 1 K at 10 hPa.

12.4.3 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 K. The temperature coefficient is positive at temperatures below the Curie point and negative at temperatures above the Curie point. Sensors can now have a diameter of about 0.1 mm. The wire thermocouple measures the change in capacitance between two fine platinum wires separated by a glass ceramic (see Turtiainen et al., 1995). This sensor gives improved speed of response, and solar heating errors are less than 1 K at 10 hPa.

12.4.4 Thermocouples

Copper-constantan thermocouple junctions are also used as a temperature sensor in one national radiosonde (WMO, 1989*a*). Wires of 0.05 mm in diameter are used to form the external thermocouple junction and these provide a sensor with a 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.

12.4.5 Scientific sounding instruments

Two specialized scientific temperature sounding sensors were deployed during the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*):

(a) The MTR temperature sensor uses an ultrathin tungsten wire as a sensor. The wire is 0.01 mm in diameter, 44 cm long and wound into a helical coil with a diameter of 0.2 mm and a pitch of 0.1 mm. The wire is coated with aluminium to improve reflectivity and thus reduce solar heating (see Shimizu and Hasebe, 2010). This sensor has smaller time-constants of response than the Copper-constantan thermocouple;

(b) The multithermistor radiosonde in Yangjiang was an independent instrument based on the National Aeronautics and Space Administration (NASA) Accurate Temperature Measuring (ATM) multithermistor radiosonde (see Schmidlin et al., 1995; WMO, 2006*d*). The system made measurements with three aluminized thermistors and one white and one black thermistor. In Yangjiang, the time constants of response were similar to those of the modern bead thermistors. With the measurements from the five sensors and an exact knowledge of the optical properties of the different sensor coatings, a reference temperature is derived as well as estimates of the solar and infrared radiation environments. This estimated temperature does not depend on any assumption about the backscattering from the surface and clouds, unlike other radiosonde temperature correction schemes.

The reliability of the absolute calibration and daytime corrections of these scientific systems did not prove to be better than those of the good operational radiosondes in the Yangjiang test.

12.4.6 Exposure

Radiosonde temperature sensors are best exposed in a position above the main body of the radiosonde (but below the body of a dropsonde). Thus, 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 long-term stability of operation, this position needs to be reproducible and must not vary from flight to flight. For good exposure at low pressures, the supports and electrical connections to the sensor should be thin enough so that heating or cooling errors from thermal conduction along the connections are 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 the 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. Evaporation of water or ice from the sensor when emerging from a cloud into drier layers will cool the sensor below true ambient temperature. 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.

12.4.7 Temperature errors

Errors in older radiosonde types widely used in the period 1980–2000 are discussed in more detail in WMO (2015b).

12.4.7.1 Calibration

Temperature errors related to calibration during an ascent may result from:

(a) Errors in factory calibration. This can occur from time to time and is one of the reasons the radiosonde measurements should be checked on the ground before launch;

(b) Small changes in the sensor, such as the stray capacitance associated with a capacitative sensor or in the electrical connections to the sensor;

(c) Instabilities in the radiosonde transducer system and references. This is possible during storage or during the ascent. Sensor or transducer drift during storage can usually be partially corrected during data processing, using adjustments based on pre-flight ground checks.

ELEMENT 11: Floating object (Automatic)

Table 12.6. Systematic error, sonde error and uncertainty (k = 2) at night from the WMO international radiosonde comparisons and other associated tests (using the NASA-ATM multithermistor reference as an arbitrary reference for systematic offsets where available)

TABLE: Table horizontal lines

Temperature sensor	*System error (K)*				*Sonde error*		*Uncertainty (k = 2)*		
Pressure (hPa)	*300*	*100*	*30*	*10*	*30*	*10*	*100*	*30*	*10*
Rod thermistor, white paint, MRZ (Russian Federation)	0.2±0.5	0.2±0.5	−0.3±0.7	−0.8±0.7	1	1	1–1.7	1–2	1.1–2.5
Copper-constantan thermocouple, Meteolabor (Switzerland)	0.1±0.1	0±0.1	−0.1±0.2	−0.1±0.2	0.3	0.4	0.3–0.4	0.3–0.6	0.4–0.7
Wire thermo-capacitor, Vaisala RS92 (Finland)	0.05±0.1	0.05±0.1	0.07±0.2	0.07±0.2	0.2	0.3	0.2–0.4	0.2–0.5	0.3–0.6
Chip thermistor, Lockheed Martin Sippican (USA)	0±0.1	−0.05±0.2	−0.07±0.2	−0.07±0.2	0.2	0.3	0.2–0.4	0.2–0.5	0.3–0.6
Bead thermistor,[a] aluminized	0±0.2	0.1±0.2	0.1±0.2	0.2±0.2	0.2	0.4	0.2–0.5	0.2–0.5	0.4–0.8
NASA-ATM multi-thermistors,	Bias assumed to be within ±0.1 K				0.2	0.2	0.2–0.3	0.2–0.3	0.2–0.3

used by
F. Schmidlin

END ELEMENT

Table 12.6 summarizes the relative performance of temperature sensors at night for different temperature sensors in operation in 2013. The results represent the typical performance averaged over a minimum of at least 15 test flights. The absolute uncertainty of the reference at night was probably better than 0.3 K, with NASA and Sippican multithermistor radiosondes agreeing as well as can be expected from the error analysis.

Where a range of systematic errors has been attributed to a radiosonde type, the range represents the spread in systematic difference found in a number of tests and also takes into account the range of likely performance up to 30 hPa estimated from radiosonde monitoring (WMO, 2003). As modern sensors have aluminized coatings, infrared errors are very small, and any spread in the performance is mainly down to the long-term consistency of factory calibration, small instabilities in the sensors, perhaps depending on the atmospheric structure and internal temperature of the radiosonde electronics, and so on. It is difficult to differentiate between the best systems in Table 12.6 as similar errors have been attributed to the sensors. The reproducibility of the temperature measurements can be measured relatively easily, but it is not currently possible to ascertain the systematic bias better than the limits shown in the table. Large-scale tests in the tropics have not given the same results for systematic bias as those in Europe, so the values shown are an average between the two conditions with the range of values necessary to encompass both sets of results.

Sonde errors are only quoted for pressures of 30 hPa and 10 hPa in Table 12.6 since, for most modern temperature sensors, sonde errors show little variation between the surface and 30 hPa, although some systems had problems near the tropopause (WMO, 2011*b*).

The Indian MKIII radiosondes have not performed good-quality temperature measurements for many years, but in this case, the poor reproducibility was not just the result of sensor performance, but also of instability in the radiosonde electronics during the ascent, resulting in effective changes in sensor calibration so that the data were degraded by the radiosonde system itself. Sonde errors for this radiosonde at 100 hPa have been in the range of 2 to 4 K for many years (WMO, 2003), although the uncertainties found from the sensors in Phase II of the WMO Radiosonde Comparison (WMO, 1987) were very much smaller than this.

12.4.7.2 Thermal lag

Most modern radiosonde temperature sensors are fast enough to not require significant correction for thermal lag errors in the troposphere and lower stratosphere.

12.4.7.3 Radiative heat exchange in the infrared

Most 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. 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. Luers and Eskridge (1998) provide a good example of users who tried to model the solar and infrared radiation errors on radiosondes in use in the 1990s.

Infrared errors affect both day and night observations. The effects of infrared heat exchange errors at night can be seen in the measurements of the rod thermistors (used on the Russian radiosonde) in Table 12.6. 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, 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. Additional information on the effects of infrared errors in the past can be found in WMO (2015b).

The use of white paint on the temperature sensor should be discontinued as soon as possible so that variation in systematic temperature error from infrared errors will then be negligible across the radiosonde network.

12.4.7.4 Heating by solar radiation

All radiosonde temperature sensors will have heating errors in daytime caused by incident solar radiation, including backscattered radiation from clouds and the surface. Table 12.7 shows the day–night differences associated with the temperature measurements of the radiosondes considered in Table 12.6. These values were derived mostly from the software corrections used for daytime temperatures by each system for solar elevations between 30° and 80°. Temperature sensors of the Russian radiosonde had relatively poor thermal isolation from supporting structures, which could often be heated more than the sensor itself, and so the Russian radiosondes also had large day–night differences at upper levels.

ELEMENT 12: Floating object (Top)

Table 12.7. Day–night differences for selected temperature sensors from the WMO international radiosonde comparisons and other associated tests

TABLE: Table horizontal lines

Temperature sensor	*Systematic error (K)*			
Pressure (hPa)	*300*	*100*	*30*	*10*
Rod thermistor, white paint, MRZ (Russian Federation)	1	1.8	3.3	5.1
Copper-constantan thermocouple, Meteolabor (Switzerland)	0.5[a] 0.3[b]	0.75[a] 0.5[b]	1.1[a] 0.75[b]	1.8[a] 1[b]
Chip thermistor, Lockheed Martin Sippican (USA)	0.3	0.5	0.8	0.95
Wire thermocapacitor, Vaisala (Finland)	0.15	0.3	0.5	0.8
Bead thermistor,[c] aluminized	0.2 – 0.5	0.3 – 1.1	0.4 – 1.5	0.6 – 2.3

Notes:

a As used in WMO (2011*b*)

b As revised in subsequent tests (Philipona et al., 2013)

c Summary of the range of results from other radiosonde systems using bead thermistors in the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

END ELEMENT

In all modern operational radiosonde systems, software corrections are applied during data processing to compensate for the solar heating (see Table 12.7). 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 solar heating models, and possibly laboratory testing. 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 sunrise or sunset flights. A simple correction scheme will work effectively only 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 with average atmospheric conditions during flight. In such circumstances, software corrections based on average conditions will be up to 30 % too large. On the other hand, in ascents over thick upper cloud with very high albedo or over desert conditions, backscattering may be much larger than usual and the software correction will underestimate the required correction.

Table 12.8 contains a review of the systematic and sonde errors in most modern radiosonde types. In the systematic errors derived from the test in Yangjiang, China (WMO, 2011*b*), it was assumed that zero systematic bias in Yangjiang was halfway between Vaisala/MODEM and LMS/multithermistor at 30 and 10 hPa. This is because subsequent testing in the United States has not shown significant errors in the multithermistor system used in Yangjiang, that is to say, there was some real atmospheric diurnal variation in temperature between 30 and 10 hPa in Yangjiang, with a probable amplitude of about 0.15 K. In the estimates of the range of systematic error in Table 12.8, it has been assumed that the standardized software correction schemes produce a range of possible systematic bias of ±30 %. During a particular radiosonde test, the radiative conditions (cloud, surface albedo) do not usually change much, so the illusion is given that the systematic bias obtained has low errors. However, a test performed at another location can give systematic errors that differ by much more than the sonde error found in the individual test.

ELEMENT 13: Floating object (Automatic)

Table 12.8. Systematic error, sonde error and uncertainty (*k* = 2) for selected temperature sensors in the day from WMO international radiosonde comparisons and other associated tests, and from operational monitoring as in WMO (2003)

TABLE: Table horizontal lines

Temperature sensor	*Systematic error (K)*			*Sonde error*			*Uncertainty (k = 2)*		
Pressure (hPa)	*100*	*30*	*10*	*100*	*30*	*10*	*100*	*30*	*10*
Rod thermistor, white paint, MRZ (Russian Federation)	0.7±0.5	0.5±1	−0.7±1.3	1	1.2	1.5	1.2–2.2	1.2–2.7	1.5–3.5
Copper-constantan thermo-couple, Meteolabor (Switzerland)	−0.2[a] −0.05[b]	−0.5[a] −0.2[b]	−0.8[a] 0[b]	0.4	0.4	0.8	0.6	0.9	1.5
Wire thermo-capacitor, Vaisala (Finland)	0±0.2	−0.2±0.2	−0.3±0.3	0.4	0.4	0.4	0.4–0.7	0.4–0.9	0.4–0.9

Chip thermistor, Lockheed Martin Sippican (USA)	–0.1±0.2	0.2±0.2	0.3±0.3	0.3	0.3	0.4	0.3–0.6	0.3–0.8	0.4–1.0
Bead thermistor,[c] aluminized	0.1±0.2	0±0.3	0±0.5	0.4–0.8	0.4–1.3	0.4–1.7	0.5–1.0	0.8–1.6	0.4–2.3
Multi-thermistor	±0.2	±0.2	±0.3	0.3	0.3	0.4	0.3–0.5	0.4–0.6	0.4–0.7

Notes:

a As used in WMO (2011*b*)

b As revised in subsequent tests (Philipona et al., 2013)

c Summary of the range of results from other radiosonde systems using bead thermistors in the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

END ELEMENT

The sonde errors for all radiosondes are larger in daytime than in night-time conditions (see Tables 12.6 and 12.8). During ascent, radiosondes swing and rotate like a pendulum suspended from the balloon, so the absorption cross-sections of the sensor change as the sensor rotates. Also, air heated by contact with either the sensor supports or the radiosonde body may flow over the external sensor from time to time. If these possibilities have not been prevented in the design (for example, if the temperature sensor is mounted close to the radiosonde body, perhaps halfway between the top and the bottom), much larger sonde errors will result in daytime. Backscattered radiation varies from flight to flight with changing cloud cover and also contributes to the increase in daytime sonde errors.

When a support frame surrounds the temperature sensor, air heated by contact with the frame passes over the sensor in part of the pendulum cycle, producing positive pulses in the reported temperature as the radiosonde moves around in flight. These pulses can be as large as 1 K at 10 hPa. The heating pulses can be readily recognized when flying radiosondes on the rigs used in WMO radiosonde comparisons since the radiosondes rotate in a very regular fashion during the flight. In this situation, suitable raw data filtering can remove the positive pulses to some extent. Thus, the filtering applied to the basic observations of several systems must also be taken into account when investigating daytime radiosonde temperature errors.

The range of systematic errors in daytime measurements shown in Table 12.8 should be smallest for the radiosonde systems with smallest day–night differences. Given that most of the increase in uncertainty relative to night-time measurements comes from poor sensor position relative to the radiosonde body and from poor design of the sensor supports, it is hoped that most of the modern radiosondes with the larger errors and day–night differences in Table 12.7 will be improved within a few years of the Yangjiang intercomparison. Thus, the results of Yangjiang represent a snapshot of performance at the time, and radiosondes with significant systematic errors in Yangjiang will all have been modified to some extent within a couple of years of completion of the test. For example, the radiation errors of the Swiss radiosonde have been revised through additional testing and the solar heating correction is now reduced as shown. This would eliminate the negative bias seen in the daytime results in WMO (2011*b*) as represented in Table 12.8.

The WMO intercomparison tests were performed with the radiosondes suspended at least 30 m and most commonly 40 m under the balloon. However, many national networks, such as China, Japan and the Russian Federation, have used much shorter suspensions which will produce additional daytime bias and increased sonde errors compared to those quoted in Tables 12.7 and 12.8, especially at pressures lower than 30 hPa.

12.4.7.5 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 % 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 will cause 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.

12.4.7.6 Representativeness issues

Representativeness issues are discussed in WMO (2015b).

12.5 RELATIVE HUMIDITY SENSORS

12.5.1 General aspects

Operational relative humidity measurements worldwide have a wide range of performance (from good to poor) as all the sensor types listed in Table 12.10 are still in use in some national networks in 2013. The most widely used sensor is the heated twin thin-film capacitor. This sensor is mounted externally, without a cover, on a boom which holds it above the top of the radiosonde body. The other modern thin-film capacitors are usually deployed externally on a boom with an aluminized cover to protect against contamination from precipitation and minimize solar heating of the humidity sensor. Carbon hygristor sensors are usually mounted in some type of protective duct in the radiosonde. The use of carbon hygristors is decreasing. Goldbeater’s skin sensors are too inaccurate and limited in coverage in the vertical to meet the requirements of modern users, but are still in use in one national network. The goldbeater’s skin is also mounted in some type of protective duct.

ELEMENT 14: Floating object (Automatic)

Table 12.9. Variation of saturation vapour pressure over a water surface as a function of temperature after Sonntag (1994)

TABLE: Table horizontal lines

Temperature (°C)	*Saturation vapour pressure (hPa)*
40	73.9
30	42.5
15	17.1
0	6.1
−15	1.92
−30	0.51

−45	0.112
−60	0.019 5
−75	0.002 5
−90	0.000 23
−100	0.000 036

END ELEMENT

A good modern radiosonde relative humidity sensor should be able to measure relative humidity to a useful accuracy at all temperatures from 40 °C down to about −70 °C. Temperatures are lower than this near the tropical and subtropical tropopause, and radiosonde sensors can make useful measurements at these temperatures provided that certain corrections are applied (see below). However, the most reliable practical method of measuring water vapour at these lowest temperatures is with a frost-point hygrometer (see Vömel et al. (2007*a*) and the results from the WMO Intercomparison of High Quality Radiosonde Systems (WMO, 2011*b*)). Table 12.9 shows the range of saturated water vapour pressures with respect to a water surface that must be resolved to provide relative humidity measurements at all levels. At temperatures below 0 °C, relative humidity sensors should be calibrated to report relative humidity with respect to a water surface.

The saturation with respect to water cannot be measured much below −50 °C, so manufacturers should use one of the following expressions for calculating saturation vapour pressure relative to water at the lowest temperatures – Wexler (1976, 1977), Hyland and Wexler (1983) or Sonntag (1994) – and not the Goff-Gratch equation recommended in earlier WMO publications. Saturation vapour pressure in ice clouds at the lowest temperatures in the tropical upper troposphere will be about 50% of the saturation vapour pressure with respect to a water surface in Table 12.9.

Satisfactory relative humidity sensor operation becomes extremely difficult at very low temperatures and pressures. The free exchange of water molecules between the sensor and the atmosphere becomes more difficult as the temperature falls. Also, 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. For instance, if a positive systematic bias of 5% relative humidity is caused by contamination at −60 °C, this would become a positive systematic bias of 40 % relative humidity at −75 °C unless the contamination is ventilated away.

In the lower stratosphere and upper troposphere, water vapour measurements should be evaluated in terms of mixing ratio as well as relative humidity. Figure 12.4 shows the variation of temperature, relative humidity and mixing ratio with height, measured by four different radiosonde sensors in the WMO Intercomparison of High Quality Radiosonde Systems (WMO, 2011*b*). Just under the tropopause, relative humidity was slightly higher than saturation, but the water vapour mixing ratio was close to the minimum, having dropped rapidly with temperature, as would be expected from Table 12.9. Where the temperature rises above the tropopause, the two relative humidity sensors with slower response (grey) show much higher water vapour mixing ratio than is realistic. The corrected sensor and the chilled-mirror hygrometer (black) show a short-lived maximum in water vapour mixing ratio immediately above the tropopause. This is unlikely to be real and suggests that the relative humidity reported by the black sensors in this layer between minutes 48.4 and 50 are too high by up to a factor of 2.5. This is probably the result of contamination of the payload or the radiosonde sensing area, and not a calibration issue. Contamination could have occurred earlier in the flight between minutes 33 and 38 after passing through a thick layer of cirrus cloud detected by the cloud radar (not shown in Figure 12.4).

ELEMENT 15: Floating object (Automatic)
ELEMENT 16: Picture inline fix size
Element Image: 8_I_12-4_en.eps
END ELEMENT

Figure 12.4. Temperature, relative humidity and water vapour mixing ratio presented as a function of time into flight, from flight 56 of the WMO Intercomparison of High Quality Radiosonde Systems. The grey measurements are from radiosondes with capacitative sensors, uncorrected for slow response time. The black measurements are from a heated twin capacitor sensor (corrected for time constant of response) and a frost-point hygrometer. (The frost-point hygrometer shows more variation with time in relative humidity and mixing ratio than the heated twin capacitor.)

END ELEMENT

The rate of response of the relative humidity sensors can be defined as:

$$dU_e/dt = -1/\tau \cdot (U_e - U) \qquad (12.17)$$

where U_e is the relative humidity reported by the sensor, U is the actual relative humidity and τ is the time constant of response.

A further complication is that the relative humidity sensor reports relative humidity for the temperature of the sensor itself. If this differs from the true atmospheric temperature, then an additional error is introduced because of the thermal lag of the humidity sensor relative to the air temperature. Modern humidity sensors have become much smaller than in the older radiosonde types to minimize this problem, and the temperature of the sensor is in any case measured directly in many, but not all, widely used modern radiosondes.

ELEMENT 17: Floating object (Top)

Table 12.10. Time constants of response τ (in seconds) of relative humidity sensors

TABLE: Table horizontal lines

Humidity sensor	*In use*	*τ at 20 °C*	*τ at 0 °C*	*τ at –20 °C*	*τ at –40 °C*	*τ at –70 °C*
Heated twin thin-film capacitor, no cap	2004	< 0.15	0.4	2	10	80
Other single thin-film capacitors covered with cap	2000–	0.1 – 0.6	0.6 – 0.9	4 – 6	15 – 20	150 – 300[a]
Carbon hygristor	1960–	0.3	1.5	9	20	Not reliable
Goldbeater’s skin	1950–	6	20	100	> 300	Not usable
Frost-point hygrometer, CFH	2003– for science		< 2[b]	< 4[b]		< 25
Chilled-mirror hygrometer, Snow White at night	1996– for science		< 2[b]	< 4[b]		< 25

Notes:

a Values derived from a comparison with hygrometers, from the WMO Intercomparison of High Quality Radiosonde Systems (WMO, 2011*b*); may include problems with the ventilation of the caps covering the sensor.

b Value estimated from an in-flight comparison with best quality radiosonde relative humidity sensors, from WMO (2011*b*).

END ELEMENT

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 a temperature sensor. This can be seen in Table 12.10, where approximate values of the time constant of response of two older and three modern sensor types are shown. In the case of the goldbeater's skin, the time constant of response quoted is for changes between about 70 % and 30 % relative humidity. The time constants of response of the goldbeater's skin sensors are much larger at a given temperature if measuring high or low relative humidity. The values for the twin thin-film capacitor (Vaisala RS92) in this table differ from those in Miloshevich et al. (2004) and were taken from updated information supplied by the manufacturer.

Two profiles of radiosonde temperature and relative humidity are shown in Figures 12.5. and 12.6. Figure 12.5 is an example of a radiosonde ascent in the United Kingdom, where the measurements from two different sensors were combined. Sudden changes in relative humidity with height occur on many flights and were observed here by both radiosonde types. The very dry layers in particular are associated with temperature inversions. The existence of these very dry layers is accepted as correct, but in the past they were considered erroneous because the earlier sensors could not measure them well. In this case, the rate of change of relative humidity with height above the lowest inversion was 6 % relative humidity per second. Thus, modern sensors offer advantages to those who need a detailed knowledge of the variation of atmospheric refractive index with height, which is significant for radio propagation. At mid-levels, rates of change of 3 % relative humidity per second are often found.

ELEMENT 18: Floating object (Top)
ELEMENT 19: Picture inline fix size
Element Image: 8_I_12-5_en.eps
END ELEMENT

Figure 12.5. Average of simultaneous measurements at first intervals by two radiosondes suspended together under one balloon, with measurements made at night

END ELEMENT

Miloshevich et al. (2004) proposed a method for correcting the slow time-constant of response in humidity measurements based on the equation:

$$U = U_e(t_2) - U_e(t_1) \cdot X / (1 - X) \qquad (12.18)$$

where U is the true ambient relative humidity, U_e is the reported relative humidity for times t_1 and t_2, U is assumed not to change significantly between t_1 and t_2 (limiting the size of the time step used), and $X = e^{-(t_2 - t_1)/\tau}$, where τ is the time constant of response of the relative humidity sensor.

For the algorithm to give satisfactory results, the data used must be as free as possible of anomalous data, noise and so on. Therefore, some form of quality control has to be applied to the basic observations and to other corrections (such as for solar heating of the humidity sensor) before the time constant of response correction is attempted. This correction cannot retrieve exact detail of the vertical profile of relative humidity at a much higher temporal resolution than the time constant of response of the sensor. It generates a smoothed vertical profile, with higher rates of change of relative humidity than in the original measurements, but any detail in the profile at time steps much smaller than the time constant of response should be treated with caution. As seen in Miloshevich et al. (2004), for a given original measurement there are quite a few possible answers, consistent with the known time-constants of response. The type of smoothing applied to the original data influences the retrieved profile, so the smoothing used needs to be well documented and the assumptions made in the use of the algorithm need to be explained to the users.

From the examples seen in Yangjiang (WMO, 2011*b*, Annex D), it was concluded that to report the relative humidity structure near the tropical tropopause, the humidity sensing system should have a time constant of response of 3 min or better, so that the adjustments for a slow time-constant of response are not too large and are not merely amplifying errors from noise in the measurements or from water/ice contamination.

Figure 12.6 illustrates the magnitude of the adjustments in a relative humidity profile for a sensor with a time constant of response of about 80 s at –70 °C and which was observing in the tropical upper troposphere during the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*). The corrected profile in Figure 12.6 is clearly much smoother than the relative humidity profiles measured in the upper troposphere by the chilled-mirror hygrometers in Figure 12.4. In Yangjiang, where corrections for slow response were applied, the result looked reasonable in about 65 % of the cases and quite wrong the rest of the time. Further testing of this type of adjustment and the type of smoothing applied seems to be justified at this time.

ELEMENT 20: Floating object (Automatic)
ELEMENT 21: Picture inline fix size
Element Image: 8_I_12-6_en.eps
END ELEMENT

Figure 12.6. Twin thin-film capacitor measurement in the upper troposphere at night in Yangjiang, China, presented as a function of time into flight, showing the humidity profile measured directly by the sensor (black) and then corrected for time constant of response errors (grey)

END ELEMENT

During the Yangjiang test, the highest rates of change observed in the troposphere/stratosphere transition were about 30 % relative humidity over about 30 seconds. Thus, at the moment even the fastest operational radiosonde relative humidity sensor cannot define the true height of the rapid drop in humidity at the tropical tropopause without correction. Corrections to the height of the top of the humid layer in Yangjiang were found to be in the range of 200 to 500 m. However, the two scientific sounding instruments in Yangjiang had faster response and could resolve this height better when the instruments were functioning correctly (see Table 12.10).

12.5.2 Thin-film capacitors

Capacitive thin-film sensors are now used in nearly all modern radiosonde designs. These sensors rely on the variation of the dielectric constant of a polymer film with ambient water vapour pressure. The dielectric constant is proportional to the number of water molecules captured at binding sites in the polymer structure. The lower electrode of the capacitor is usually formed by etching a metal-coated glass plate, with dimensions of either 5 by 3 mm or 4 by 1.5 mm and a thickness of 0.55 or 0.2 mm. There is often a trade-off in thickness, with a thinner film having a faster time-constant of response at low temperatures but perhaps less stability in performance over time. The upper electrode is vacuum-evaporated onto the polymer surface and is permeable to water vapour. Sensor capacitance is usually a nearly linear function of relative humidity, and the temperature dependence of calibration is not large. These sensors are always mounted on a supporting boom which should expose the sensor above the top of the radiosonde or a long way away from the radiosonde body to the side.

The calibration of these 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.

Contamination from rain, water drops in clouds or ice accretion has to be driven off if no protective cap is used with the sensor. This can be achieved by heating the sensor well above ambient temperature. Twin sensors are used, with one sensor measuring while the other is heated and then cooled back to normal operation (Paukkunen, 1995). The twin sensors are mounted about 1 cm apart. These particular sensors also have a thin hydrophobic coating to minimize contamination from liquid water. As the sun shines directly on the sensors and their supports, the humidity sensors warm up relative to the correct temperature, particularly in the upper troposphere. This warming effect needs to be compensated in order to achieve accurate humidity measurements. One method is to directly measure the temperature of the humidity sensor and use this information for the compensation. In early versions of this sensor system, the surrounding printed circuit board was not coated with a highly reflective surface, and the humidity sensor was warming too much in the upper troposphere in daytime. So, all the support surfaces were then aluminized, and this was first tested in Mauritius (WMO, 2006*a*) and then as an operational product in Yangjiang, China (WMO, 2011*b*). Initially, the manufacturer advised users to use this sensor with correction software for slow time-constants of response at low temperatures and a correction for solar heating of the sensor in the daytime. However, the most recent version of the manufacturer’s system software applies these corrections automatically by default.

Four radiosondes in the WMO Intercomparison of High Quality Radiosonde Systems (WMO, 2011*b*) used another sensor, manufactured by E+E Elektronik. This sensor was always deployed with a protective cap to minimize contamination. This cap usually has a highly reflective coating, so the sensor does not warm up too much in the daytime in the upper troposphere. Also, the sensor supports and the cap must not be hygroscopic, otherwise outgassing from these surfaces will cause significant errors. Some of the manufacturers apply corrections for slow time-constants. With this sensor, the errors from a slow time-constant are larger than with the twin sensor. Most of the radiosondes using this sensor used an additional thermistor to measure the temperature of the humidity sensor directly, rather than assuming the humidity sensor was at the same temperature as the corrected temperature sensor.

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 (of approximately 1 mm thick, 60 mm long and 18 mm wide) 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 % relative humidity is about 100 times as large as the resistance at 30 % 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 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 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.

It should be noted that the sensors do not seem to have stable calibration at high humidity, and the reproducibility of the sensor measurements at lower humidity is often poor. In the WMO Radiosonde Humidity Sensor Intercomparison (WMO, 2006*b*), it was shown that if the sensors (supplied by the main hygristor manufacturer) were kept at a high humidity for several hours, the calibration of the sensor changed irreversibly. Also, the sensors did not measure low humidity (less than 20 %) in a reproducible fashion (see Wade, 1995), and measurements from these sensors misled many meteorologists into thinking that relative humidity lower than about 20 % did not occur in the lower troposphere.

12.5.4 Goldbeater's skin sensors

Goldbeater's skin (beef peritoneum) is still being used. The length of a piece of goldbeater's skin changes by between 5 % to 7 % for a change in humidity from 0 % to 100 %. While useful measurements can be obtained at temperatures higher than −20 °C, sensor response becomes extremely slow at temperatures lower than this (see Table 12.10). Goldbeater's skin sensors also suffer from significant hysteresis following exposure to low humidity.

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 sensor by keeping it in a saturated atmosphere for 20 min both before calibration and before use. Calibration should be carried out during a relative humidity cycle from damp to dry conditions. The sensor must be protected from rain during flight.

The time constant of response of the sensor is much higher than the values quoted in Table 12.10 at very high and very low humidity (McIlveen and Ludlam, 1969). Thus, it is difficult to avoid large 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 Scientific sounding instruments

Two specialized scientific water vapour sounding instruments were successfully deployed during the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*). These systems were not as inherently reliable as the operational radiosondes, but when they worked correctly they were extremely useful in identifying the limitations of the operational radiosondes.

(a) The Cryogenic Frost-point Hygrometer (CFH) (Vömel et al., 2007*a*) is a chilled-mirror hygrometer. The CFH uses a feedback loop that actively regulates the temperature of a small mirror, which is coated with ice (or dew in the lower troposphere). In the feedback loop, an optical detector senses the amount of ice covering the mirror, and the feedback controller regulates the temperature of the mirror such that the amount of ice remains constant.

    When the feedback controller is operating correctly, the mirror temperature is equal to the frost-point temperature, and if there is no internal ice/water contamination, then the frost-point temperature of the atmosphere. The inlet tubes to the CFH are stainless steel and 17 cm long with a diameter of 2.5 cm, mounted directly above and below the hygrometer. This is intended to ensure that contamination from the air passing through the hygrometer is minimal, and the test results in Yangjiang confirmed that the CFH contamination was lower than experienced by the Snow White chilled-mirror hygrometer in the upper troposphere and lower stratosphere.

    Time constants of response vary from a few seconds in the lower troposphere and increase with height up to about 20 to 30 s in the stratosphere. Thus, in the lower troposphere, the CFH time constant of response is not distinguishable from the best operational radiosondes. However, in the upper troposphere and lower stratosphere, it is faster in response than the best operational radiosondes. The main measurement uncertainty in CFH measurements is the stability and drift of the feedback controller. Thus, the total measurement uncertainty is estimated to be about 0.5 K in dewpoint or frost-point temperature, corresponding approximately to about 9 % relative humidity at the tropical tropopause and 4 % relative humidity in the lower troposphere.

    The CFH uses a cold liquid at temperatures below −100 °C to cool the mirror during flight. Preparation and handling of this coolant before flight requires training and special handling procedures to avoid personal injury.

Correction schemes (solar heating, time constant) applied to the operational radiosonde relative humidity in the upper troposphere have benefited from comparisons with CFH measurements, for example the unpublished comparisons of the LAPBIAT Upper Troposphere Lower Stratosphere Water Vapour Validation Project (LAUTLOS-WAVVAP) in Sodankyla, Finland (2004), and the Lindenberg Upper-air Methods Intercomparison (LUAMI) in Lindenberg, Germany (2008).

(b) The Snow White hygrometer also uses the chilled-mirror principle for sensing water vapour (see Fujiwara et al., 2003). However, this uses a Peltier cooler to cool its mirror. There are two versions of the sensing system. The daytime mirror hygrometer was mounted in an internal duct in the sensing system. This configuration did not prevent contamination, thus affecting the accuracy of the measurements below temperatures of about −50 °C, and was only used on a few flights in Yangjiang. In the night-time version, the mirror hygrometer was mounted above the radiosonde body. Thus, the night-time mirror hygrometer had little direct protection against contamination, but a very good exposure to ambient conditions. In Yangjiang, the Snow White night-time system was able to measure dewpoint temperatures down to below −75 °C on 70 % of the night-time flights. Two daytime flights suffered bad contamination near thunderstorms in the afternoon, but night-time Snow White sensing systems were not significantly contaminated in upper cloud because on this occasion ascent conditions were favourable to the Snow White operation. However, contamination around the hygrometer structure limited the use of Snow White to heights less than 18 km, just above the tropical tropopause in Yangjiang. Snow White has the same advantage as CFH in terms of the time constants of response that are much smaller than the operational humidity sensors in the upper troposphere.

It is necessary to have a skilled operator who can recognize when the mirror film changes phase from water to ice (Snow White must also be flown with a good operational humidity sensor). The operator must also be able to detect possible failure modes (such as the mirror losing its ice film) in the middle and upper troposphere. Identifying when contamination has corrupted the hygrometer measurements is a skill required for both Snow White and CFH.

The two chilled-mirror hygrometers have the advantage over operational relative humidity sensors of being sensitive in the upper troposphere and lower stratosphere down to the lowest temperatures, provided that contaminated measurements are recognized and excluded. Their measurements also do not have significant day–night differences in performance. Therefore, as working references, their measurements have proved to be the best method of identifying these differences. Comparison with the chilled-mirror measurements has allowed the development of correction procedures or changes in operational procedures to produce better-quality operational measurements in the middle and upper troposphere.

Sensors in ducts do not provide the best method of observing relative humidity structure through rain and low cloud, so it is unwise to treat the chilled mirrors as more reliable than the best operational radiosonde sensors in the lower troposphere.

12.5.6 Exposure

Rapid changes in relative humidity greater than 25 % are common during radiosonde ascents. Accurate measurements of these changes are significant for some users. Accurate measurements require that the humidity sensor is well ventilated, but the sensor also needs to be protected as far as possible from the 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, are mounted on an external outrigger. The sensor may be covered by a small protective cap, or the sensors may be heated periodically to drive off contamination from water or ice in cloud or fog. The design of the protective cap may be critical, and it is essential to ensure that the cap design is such that the humidity sensor is well ventilated during the radiosonde ascent.

Larger sensors were usually mounted in 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 airflow into the duct guarantees 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. Particular care is required in duct design if contamination in upper cloud is to be avoided.

Protective covers or duct coatings should not be hygroscopic. For examples, see the stainless steel inlet pipes used by CFH or the aluminized sensor mounts of some operational radiosondes.

12.5.7 Relative humidity errors

Errors in older radiosonde types widely used between 1980 and 2000 are discussed in more detail in WMO (2015b).

12.5.7.1 General considerations

Operational relative humidity sensors have improved greatly compared to the sensors in use before the 1980s, especially at low temperatures in the middle and upper troposphere. Relative humidity observations at temperatures lower than –40 °C were not reported in most of the early radiosonde systems, and relative humidity reports at such temperatures were not in significant use until about 2000.

Real-time operational assessment of radiosonde relative humidity measurements by users is not very extensive, and methods need to be developed for providing information to the manufacturers on the calibration performance of the sensors. For example, records could be provided of the relative humidity reported when the radiosonde was known to pass through low cloud, or statistics could be sent of the pre-flight ground checks. When testing radiosondes, it should not be assumed that the uncertainty in the measurements is the same for all relative humidity bands. Non-uniform performance across the relative humidity range was still found for many systems in the WMO Intercomparison of High Quality Radiosonde Systems (WMO, 2011*b*). However, the better systems are now much closer to uniformity at all relative humidity than what was found at the start of the WMO radiosonde comparison series in 1984. During manufacture, calibrations on individual sensors are often performed only 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 have often varied by several per cent in relative humidity from batch to batch, as can be seen from measurements in low-level cloud (Nash et al., 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 the sensors during storage. In addition, the thickness of the film in some thin-film capacitors is not always the same, so the thicker sensors are sometimes quite unresponsive to humidity changes at low temperatures, while the majority of the sensors of the same type respond well in the same conditions.

In the following sections, errors are first considered for temperatures greater than –20 °C, where both older and newer sensors were expected to work reliably. Before 1990, most of the radiosondes in use had significant problems with measurements at temperatures lower than –30 °C. Thus, only the errors of the more modern sensor types are considered for the temperature bands between –20 °C and –50 °C, where such sensors work more reliably, and then for temperatures between –50 °C and –70 °C, where only the newest relative humidity sensors could respond quickly enough to make useful measurements. The analysis is then further divided into night-time and daytime performance. Night-time measurements may not necessarily be more reliable than those in the daytime because, in many cases, there seems to be a greater chance of contamination around the sensor at night if its ventilation is poor, while solar heating of the sensor surroundings drives off more of the contamination in the day or produces a compensating low bias in the daytime humidity.

Water vapour pressure is obtained by multiplying the saturation 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, the reported water vapour (and hence any derived dewpoint) will be in error. In a region of the troposphere where temperature is decreasing with height, the humidity sensor temperature will be higher than the air temperature reported. If the humidity sensor temperature is higher than true temperature by 0.5 K at a temperature close to 20 °C, the relative humidity reported by the sensor will be about 97 % of the true relative humidity. This will result in an error of −1.5 % at a relative humidity of 50 %. 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 % and then to 95 % of the true value.

Systematic errors in relative humidity measurements may occur because of changes in calibration during storage. This may simply be due to sensor ageing or the build-up of chemical contamination, where contamination occupies sites that normally would be open for water vapour molecules. The rate of contamination may depend on the chemicals used in manufacturing the radiosonde body or the packaging, and cannot be assumed to be the same when the manufacturing of the radiosonde body or printed circuit boards changes with time. The manufacturer's instructions regarding the storage of the sensors and preparations for use must be applied carefully. For instance, it is essential that the ground check process be performed with the Vaisala RS92 sensor before launch, since this drives off any build-up of chemical contamination and hence low bias early in the ascent.

12.5.7.2 Relative humidity at night for temperatures above −20 °C

Table 12.11 summarizes night-time systematic differences in relative humidity at temperatures higher than −20 ºC for the most widely used sensors tested during the WMO International Radiosonde Comparison. The results shown in Table 12.11 have been limited to night flights to eliminate complications caused by solar heating. More detailed results on the earlier tests may be found in Nash et al. (1995). From 1984 until 2000, the performance of the Vaisala RS80 A-Humicap was used as an arbitrary reference linking the earlier tests in the WMO Radiosonde Comparison. More recent tests in Brazil and Mauritius have also used the Meteolabor Snow White chilled-mirror hygrometer as a working standard. Both Snow White and CFH measurements were used in the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China, and the systematic error in the reference used in these tests was probably somewhere in the range of ±2 % for the temperature range in Table 12.11.

ELEMENT 22: Floating object (Automatic)

Table 12.11. Systematic differences, sonde error and uncertainty (k = 2) of radiosonde relative humidity measurements at night for temperatures higher than −20 °C

TABLE: Table horizontal lines

Humidity sensor	*System bias (% RH)*			*Sonde error*			*Uncertainty (k = 2)*		
Relative humidity (% RH)	*80–90*	*40–60*	*10–20*	*80–90*	*40–60*	*10–20*	*80–90*	*40–60*	*10–20*
Goldbeater's skin, MRZ (Russian Federation) and RS3 (UK)[a]	−8	−1	9	12	18	16	20	19	25
Carbon hygristor,	4–10	−4–4	−20–10	10	4–16	6–20	14–20	4–20	6–40

VIZ MKII (USA)									
Twin thin-film capacitor, Vaisala RS92 (Finland)	1±2[d]	0±2	0±2	3	5	3	3–6	5–8	3–5
Thin-film capacitor, used in LMS-6[b] (USA)	−1±2	1±3	2±2	3	5	3	4–6	6–9	5–9
Other thin-film capacitors[c]	3±2	6±3	2±2	4	5	3	5–9	8–14	3–7
Snow White, Meteolabor (Switzerland)	−1	−1	−1	4	5	3	5	6	4
CFH (USA/Germany)	4[e]	3[e]	0	8	7	2	13	10	2

Notes:

a Data from dry conditions only were used in the analysis.

b Uses E+E Elektronik sensor from Austria.

c Summary of the range of results from other radiosonde systems without major design faults in the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

d Uses information from Miloshevich et al. (2009) as well as other WMO and UK tests.

e CFH seemingly had positive bias at low levels in WMO (2011*b*), similar to the situation in Miloshevich et al. (2009).

END ELEMENT

In the comparisons in Table 12.11, the time constants of response of most thin-film capacitors and the carbon hygristor were similar and fast enough to avoid significant systematic bias from slow sensor response. Goldbeater's skin is able to respond reasonably well to rapid changes in mid-range relative humidity at these temperatures. Nonetheless, the very slow response of this sensor at high and low humidity contributes to the large systematic differences in Table 12.11, with measurements too low at high relative humidity and too high at low relative humidity.

The results quoted for the VIZ MKII carbon hygristor show very wide ranges in uncertainty, especially at very low humidity. The results were different according to whether the conditions were dry or generally very moist (especially with liquid water present in cloud or rain). This seemed to be because the calibration of this newer hygristor sensor also changed when conditions were very moist (in cloud), giving a significant dry bias at lower humidities. Proposed changes in algorithms, especially at low humidity, did not result in any consistent improvement in the measurement quality. The LMS-6 radiosonde, successor to the VIZ MKII, now uses a capacitor sensor. Carbon hygristors have been in use in India and China in the last decade.

Since 2005, the majority of the modern humidity sensors have shown improved stability and protection against water contamination in cloud (contamination effects normally being short lived and not resulting in permanent offsets during the ascent), and improved reproducibility from batch to batch. Thus, the results from dry and wet conditions can now be combined, apart from in very heavy rain when no system performs reliably. Thus, for the better sensor types, uncertainties (k = 2) in the range of 5 % to 10 % seem achievable across the whole relative humidity range.

12.5.7.3 Relative humidity in the day for temperatures above −20 °C

Table 12.12 contains the summary of daytime systematic differences, sonde error and uncertainty of the radiosonde relative humidity measurements for temperatures higher than −20 °C. This table only includes information on the modern humidity sensor designs.

ELEMENT 23: Floating object (Top)

Table 12.12. Systematic differences, sonde error and uncertainty (k = 2) of radiosonde relative humidity measurements in the day for temperatures higher than −20 °C

TABLE: Table horizontal lines

Humidity sensor	*System bias (% RH)*			*Sonde error*			*Uncertainty (k = 2)*		
Relative humidity (% RH)	*80–90*	*40–60*	*10–20*	*80–90*	*40–60*	*10–20*	*80–90*	*40–60*	*10–20*
Carbon hygristor, VIZ MKII (USA)	−2±4	−3±6	0±10	7	7	10	7–13	7–16	10–20
Twin thin-film capacitor, Vaisala RS92 (Finland)	−9±2[c] −3±2[d] 1±2[e]	 −3±2[d] 0±2[e]	 −1±2[d] −1±2[e]	4 4 4	4 4 4	2 2 2	11–15 5–9 5–7	 5–9 4–6	 3–5 3–5
Thin-film capacitor, LMS-6[a] (USA)	−3±2	0±3	0±2	4	4	2	7–9	4–7	2–4
Other thin-film capacitors[b]	1±2	2±2	0±2	4	4	3	4–7	4–8	3–5
Snow White, Meteolabor (Switzerland)	−1	−1	−1	4	8	4	5	9	5
CFH (USA/Germany)	1	1	0	8	8	2	9	9	2

Notes:

a Uses E+E Elektronik sensor from Austria.

b Summary of the range of results from other radiosonde systems without major design faults in the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

c Vaisala RS92 original with a bare printed board as part of support for relative humidity sensors; values for tropics from Vömel et al. (2007*b*).

d Vaisala RS92 with fully aluminized supports but no correction for solar heating (WMO, 2006*a*).

e Vaisala RS92 with fully aluminized sensor support and correction for solar heating, in the tropics (WMO, 2011*b*).

END ELEMENT

Comparison with collocated remote-sensing observations (microwave radiometers or GPS water vapour) has confirmed that there is a day–night difference in modern radiosonde relative humidity measurements (for examples, see Turner et al., 2003; and WMO, 2006*a*, 2011*b*). The day–night difference can also be estimated independently from comparisons with the Snow White hygrometer, as Snow White measurements are relatively consistent between day and night at temperatures higher than −40 °C.

The situation with the Vaisala RS92 changed in 2006 when significant developments in sensor support designs led to changes in performance in daytime measurements. Early versions had a bare printed circuit board as part of the sensor supports. These supports heated up much more than the aluminized surfaces, and thus led to higher heating of the air passing over the humidity sensors. This was recognized as causing a problem and, by the time the WMO radiosonde comparison in Mauritius (WMO, 2006*a*) was conducted, the sensor supports had been fully aluminized, with the results corresponding to footnote “d” in Table 12.12. Thus, the measurements reported by Vömel et al. (2007*b*), performed with the original RS92 version (footnote “c”), show larger dry biases than those observed in Mauritius. This aluminization did not eliminate the solar heating problem, but did reduce the magnitude of the effect. As can be seen, this represents the main step forward in reducing the uncertainty of the Vaisala daytime relative humidity measurements at higher temperatures. In the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*), software was used to correct the daytime negative bias from solar heating.

Thus, the daytime twin thin-film capacitor measurements were optimized only after the software used in the Yangjiang comparison was introduced operationally worldwide, and the uncertainty in the daytime measurements was much worse than in the night-time measurements until the hardware and software modifications were introduced after 2006.

However, in general, uncertainties (k = 2) for the better sensor types in the range of 5 % to 10 % seem achievable across the whole relative humidity range, and day–night differences in systematic error are not usually large in this temperature range.

12.5.7.4 Relative humidity at night for temperatures between –20 °C and –50 °C

Table 12.13 contains a summary of night-time systematic differences, sonde error and uncertainty of the radiosonde relative humidity measurements for temperatures between –20 °C and –50 °C. For most radiosonde systems designed before 2000, the relative humidity sensor performance was usually influenced by the conditions experienced earlier in the flight, so the values obtained in early tests in this temperature range were not very reproducible, even when thick cloud and rainy conditions were excluded and are not considered here.

Whereas the twin thin-film capacitor and LMS capacitor had small systematic errors, this was not true of all the remaining radiosonde types in Yangjiang, where poor ventilation of the sensor under the protective cap gave rise to increased positive bias in the measurements at high and mid-range relative humidity. Not all the humidity sensors in Yangjiang could provide uncertainties (k = 2) in the range of 5 % to 10 % relative humidity in the humid conditions experienced in this temperature range.

Table 12.13. Systematic differences, sonde error and uncertainty (k = 2) of radiosonde relative humidity measurements at night for temperatures between –20 °C and –50 °C

TABLE: Table horizontal lines

Humidity sensor	*System bias (% RH)*			*Sonde error*			*Uncertainty (k = 2)*		
Relative humidity (% RH)	*60–80*	*40–60*	*10–20*	*60–80*	*40–60*	*10–20*	*60–80*	*40–60*	*10–20*
Carbon hygristor, VIZ MKII (USA)[a]	–5–0	–10 to –4	–20–10	10	8	7	10–15	12–18	17–27
Twin thin-film capacitor, Vaisala RS92 (Finland)	1±3[d]	0±3	0±2	6	6	4	6–10	6–9	4–6
Thin-film capacitor, used in LMS-6[b] (USA)	–1±2	1±3	2±2	6	6	4	6–9	6–10	4–8
Other thin-film capacitors[c]	3±10	7±8	4±4	6	8	4	6–19	8–23	4–8
Snow White, Meteolabor (Switzerland)	–2	–1	3	6	8	4	8	9	7
CFH (USA/Germany)	2	1	0	5	5	5	7	6	5

Notes:

a Data from dry conditions only were used in the analysis.

b Uses E+E Elektronik sensor from Austria.

c Summary of the range of results from other radiosonde systems with low sonde errors in the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

d Uses information from Miloshevich et al. (2009) as well as other WMO and UK tests.

12.5.7.5 Relative humidity in the day for temperatures between −20 °C and −50 °C

Table 12.14 contains a summary of daytime systematic differences, sonde error and uncertainty of the radiosonde relative humidity measurements for temperatures between −20 °C and −50 °C.

ELEMENT 24: Floating object (Top)

Table 12.14. Systematic differences, sonde error and uncertainty (*k* = 2) of radiosonde relative humidity measurements in daytime for temperatures between −20 °C and −50 °C

TABLE: Table horizontal lines

Humidity sensor	*System bias (% RH)*			*Sonde error*			*Uncertainty (k = 2)*		
Relative humidity (% RH)	*60–80*	*40–60*	*10–20*	*60–80*	*40–60*	*10–20*	*60–80*	*40–60*	*10–20*
Carbon hygristor, VIZ MKII (USA)[a]	−8	−9	±10	10	8	7	18	17	7−17
Twin thin-film capacitor, Vaisala RS92 (Finland)	−16±4[d] −7±2[e] 2±2[f]	−5±2[e] 3±2[f]	−3±2[e] −1±2[f]	6 6 6	4 4 4	2 2 2	16−24 11−15 6−10	7−11 5−9	3−7 2−5
Thin-film capacitor, used in LMS-6[b] (USA)	−2±2	−3±3	0±2	6	8	2	6−10	8−14	2−6
Other thin-film capacitors[c]	−3±2	0±3	1±3	7	6	4	7−12	6−9	4−8
Snow White, Meteolabor (Switzerland)	0	1	1	6	8	4	8	9	7
CFH (USA/Germany)	2	1	0	5	5	5	7	6	5

Notes:

a Data from dry conditions only were used in the analysis.

b Uses E+E Elektronik sensor from Austria.

c Summary of the range of results from other radiosonde systems with low sonde errors in the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

d Vaisala RS92 original with a bare printed board as part of support for relative humidity sensors; values for tropics from Vömel et al. (2007*b*).

e Vaisala RS92 with fully aluminized supports but no correction for solar heating (WMO, 2006*a*).

f Vaisala RS92 with fully aluminized sensor support and correction for solar heating, in the tropics (WMO, 2011*b*).

END ELEMENT

The systematic errors in the twin thin-film capacitor measurements in daytime had larger negative biases than at the higher temperatures in Table 12.12. Thus, it took until about 2011 before the erroneous dry biases were removed from the daytime twin thin-film capacitor measurements and the large uncertainties in these measurements were reduced to the values found at night in Table 12.13.

In the daytime, the other sensors in the Yangjiang test did not have the significant positive biases relative to the LMS capacitor that were seen at night in Table 12.13. However, it was more difficult in this daytime temperature band to ensure that the operational radiosondes were able to measure with an uncertainty (k = 2) of between 5 % and 10 % under all conditions.

Two of the radiosonde systems in Yangjiang had very large sonde errors both day and night because of problems with sensor design, and one more system had large sonde errors in daytime only, because of poor positioning of the humidity sensor. So, obtaining good performance in this band requires significant testing and elimination of design problems that do not necessarily affect the measurements at higher temperatures very much (see WMO, 2015b).

12.5.7.6 Relative humidity at night for temperatures between –50 °C and –70 °C

Table 12.15 shows the systematic differences, sonde error and uncertainty (k = 2) for night-time measurements at temperatures between –50 °C and –70 °C for the modern sensors only. These sensors/sensing systems differ in terms of time constant of response. All have longer than optimum time-constants in the upper troposphere/lower stratosphere in the tropics, with some becoming slow at –60 °C and others at –80 °C. The chilled-mirror hygrometers are capable of working reasonably quickly at these low temperatures and have thus provided evidence on the speed of response of the operational sensors.

The sonde errors in Table 12.15 at –60 °C are generally about twice as large as those at temperatures higher than –20 °C in Table 12.11, the exception being the CFH with more reproducible measurements at upper levels than in the lower troposphere. The reference used in Table 12.15 for systematic errors cannot be defined better than ±4 %, as all the sensors including CFH (due to possible contamination) have limitations. The time constant of response corrections applied to Vaisala RS92 in 2011 only changed the systematic bias by +0.5 % RH in the 40 % to 60 % relative humidity band and –1.2 % RH in the 20 % to 40 % band. In analysing the results from the WMO Intercomparison of High Quality Radiosonde Systems, some CFH and Snow White flights had to be flagged out because of technical problems. Remember that the systematic errors in Table 12.15 are straightforward difference in relative humidity and are not presented as a percentage ratio of the relative humidity being measured.

ELEMENT 25: Floating object (Top)

Table 12.15. Systematic differences, sonde error and uncertainty (k = 2) of radiosonde relative humidity measurements at night for temperatures between –50 °C and –70 °C in the troposphere

TABLE: Table horizontal lines

Humidity sensor	*System bias (% RH)*		*Sonde error*		*Uncertainty (k = 2)*	
Relative humidity (% RH)	*40 – 60*	*20 – 40*	*40 – 60*	*20 – 40*	*40 – 60*	*20 – 40*
Twin thin-film capacitor, Vaisala RS92 (Finland)	0 ± 4[c]	1 ± 3	7	4	7 – 11	4 – 8
Thin-film capacitor, used in LMS-6[a] (USA)	1 ± 4	–1 ± 3	12	14	12 – 17	14 – 18

Other thin-film capacitors[b]	4 ± 6	5 ± 4	12 ± 8	12 ± 8	6 – 30	5 – 29
Snow White, Meteolabor (Switzerland)	−3 ± 3	−2	9	8	9 – 15	10
CFH (USA/Germany)	2	2	5	3	7	5

Notes:

a Uses E+E Elektronik sensor from Austria.

b Summary of the range of results from other radiosonde systems known to be in operational use from the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

c Uses information from Miloshevich et al. (2009) as well as other WMO and UK tests.

END ELEMENT

Table 12.15 shows that probably only two radiosonde systems were capable of providing relative humidity measurements with uncertainty in the range of 6 % to 12 % at night and at temperatures between −50 °C and −70 °C, whether cloud was present or not. WMO (2015b) showed that another four were capable of providing measurements in the range of 10 % to 20 %.

At very low humidity in the stratosphere, the expected sonde error of CFH becomes about 2 % when measuring 10 % relative humidity, and 0.4 % when measuring 2 % relative humidity, whereas operational radiosonde errors will stay near the values quoted in Table 12.15 and are thus not suitable for stratospheric measurements where fractions of a per cent relative humidity make a significant difference to the water vapour mixing ratio reported.

12.5.7.7 Relative humidity in the day for temperatures between −50 °C and −70 °C

Table 12.16 shows the systematic biases, sonde errors and uncertainty for daytime humidity measurements centred at a temperature of −60 °C. The daytime sonde errors were similar or slightly smaller than the night-time sonde errors. Thus, any increase in sonde error from solar heating was balanced by a decrease in some of the other sources of error at night, such as contamination. It appeared that the structures in the vertical were similar between day and night, but it is possible that time constant of response errors were bigger in night-time conditions, which may have influenced the difference in the sonde errors between day and night.

ELEMENT 26: Floating object (Top)

Table 12.16. Systematic differences, sonde error and uncertainty (k = 2) of radiosonde relative humidity measurements in the day for temperatures between −50 °C and −70 °C in the troposphere

TABLE: Table horizontal lines

Humidity sensor	*System bias (% RH)*		*Sonde error*		*Uncertainty (k = 2)*	
Relative humidity (% RH)	*40 – 60*	*20 – 40*	*40 – 60*	*20 – 40*	*40 – 60*	*20 – 40*
Twin thin-film capacitor, Vaisala RS92 (Finland)	−22 ± 4[c] −12 ± 3[d] 3 ± 3[e]	−14 ± 4 −7 ± 3 0 ± 3	5 5 5	3 3 3	23 – 31 14 – 20 5 – 11	13 – 21 7 – 13 3 – 6
Thin-film capacitor, used in LMS-6[a] (USA)	−4 ± 3	−3 ± 3	8	10	9 – 15	10 – 16

Other thin-film capacitors[b]	−2 ± 6	−1 ± 5	9 ± 3	11 ± 2	6 – 20	9 – 19
CFH (USA/Germany)	2	1	5	5	7	6

Notes:

a Uses E+E Elektronik sensor from Austria.

b Summary of the range of results from other radiosonde systems known to be in operational use from the Yangjiang comparison (WMO, 2011*b*). See WMO (2015b) for details of the individual radiosonde types at Yangjiang.

c Vaisala RS92 original with a bare printed board as part of support for relative humidity sensors; values for tropics from Vömel et al. (2007*b*).

d Vaisala RS92 with fully aluminized supports but no correction for solar heating (WMO, 2006*a*).

e Vaisala RS92 with fully aluminized sensor support and correction for solar heating (WMO, 2011*b*).

END ELEMENT

The system with the most pronounced negative bias in daytime was the Vaisala RS92 in its original form. The temperature sensors were heated both directly by solar heating of the humidity sensor and by air which is heated by the bare copper surfaces on the supports near the sensor and then passes over the sensor. The other systems mostly have aluminized covers, so direct solar heating is not primarily the problem. However, air heated by passing over the supports and plastic does affect the humidity sensor temperature. Some manufacturers, such as Lockheed Martin Sippican and InterMet, measure the temperature of the humidity sensor with a dedicated sensor. In the most recent tests, the Vaisala RS92 had a software correction for heating, as did the Graw system (see WMO, 2011*b*, Annex D). Values reported in cloud at very low temperatures for both systems seemed higher in the daytime than at night and much higher than was shown by Snow White or CFH. Thus, at this stage it is probable that the corrections applied to the operational radiosondes may have errors, especially in cloudy conditions, although the corrections probably bring the systematic bias closer to the correct values compared to measurements without the correction (see the Vaisala results).

Table 12.16 shows that in 2011, probably only two radiosonde systems were capable of providing relative humidity measurements with uncertainty in the range of 6 % to 12 % in daytime at temperatures between −50 °C and −70 °C, whether cloud was present or not (given that the twin thin-film capacitor had the complete set of corrections used in Yangjiang). WMO (2015b) shows another four capable of providing measurements in the uncertainty range of 10 % to 20 %.

Most of the test data used for Tables 12.15 and 12.16 have been obtained in the tropics, where the temperature band centred on −60 °C may be 4 km higher than at higher latitudes (see Figure 12.2). The systematic biases for heating error for a given temperature can be expected to have a range of values, with the lower negative biases associated with the mid-latitude operation in cloudy conditions at higher pressures and the large negative biases associated with tropical operations in clear situations.

12.5.7.8 Wetting or icing in cloud

Modern humidity sensors can get contaminated when passing through cloud, but normally the main effects of positive bias are short-lived and contamination ventilates away or, on the twin thin-film capacitor, is heat-pulsed away in the next heating cycle of the sensor. Icing in cloud can occur at temperatures much lower than −40 °C; this may not ventilate away as quickly as the contamination in the lower troposphere.

12.5.7.9 Representativeness issues

Representativeness issues are discussed in WMO (2015b).

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 the following:

(a) An aerial and radio receiver for receiving the signals from the radiosonde;

(b) Equipment to decode the radiosonde signals and to convert the signals to meteorological units;

(c) Equipment to present the meteorological measurements to the operator so that the necessary messages can be transmitted to users, as required.

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

The output of the decoder should usually be input to a computer for archiving and subsequent data processing and correction.

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. If maintenance support will mainly be provided by the manufacturer or its agents, and not by the operators, an integrated system may be the preferred choice. A system composed of individual modules may be more 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. Systems built from modules have encountered problems in the last 10 years because of the complexity of testing such systems and the problems introduced when adapting manufacturers' standard correction software to non-standard use by another processing system.

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 programmers 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 counterproductive to allow too much interpolation of data using mathematical techniques that will be quite stable when data quality is generally good, but will become unstable when data quality is generally poor. A good example of an algorithm that can become unstable when signal quality is poor is the time constant of response correction used by some manufacturers for temperature.

In the past, certain problems with signal reception and pressure errors near the launch were sometimes 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.[1] 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 which 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 was performed by highly skilled operators and test staff, until the software had become thoroughly reliable in operation. The ground system software was then suitable for use by operators without any significant specialized computing skills.

The software in the ground system should be well documented and should include clear descriptions of the algorithms in use.[2] The overall system should be designed to allow sounding simulations for testing and comparison purposes. It is proposed that sets of a suitable range of 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 when the radiosonde is 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 is 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 conducted in a ventilated chamber with a 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 humidity, if necessary. If no reference psychrometer is available, 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 checked regularly in order to avoid long-term drifts in calibration errors. A suitable software adjustment of radiosonde calibration normally improves the reproducibility of the

[1] As recommended by the Commission for Instruments and Methods of Observation at its twelfth session (1998), through Recommendation 2 (CIMO-XII).

[2] See Recommendation 2 (CIMO-XII).

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 there are large discrepancies relative to the control measurements, the radiosonde may have to be rejected as falling outside 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 recommends that:[3]

(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;

(d) The sensors used as the reference should be at least as accurate as the radiosonde sensors and be calibrated regularly according to the manufacturer's instructions.

12.7.2 Deployment methods

Radiosondes are usually carried by balloons rising with a rate of ascent of between 5 and 8 m s^{-1}, depending on the specifications and characteristics of the balloon in use (see Volume III, Chapter 8). These rates of ascent allow the measurements to be completed in a timely fashion – i.e. about 40 min to reach 16 km and about 90 min 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.

[3] As recommended by the Commission for Instruments and Methods of Observation at its eleventh session, held in 1994, through Recommendation 9 (CIMO-XI).

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 15 min. 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 and transmit direct readings and operate automatically under programme control. 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 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 Volume III, Chapter 8) and on the strength and direction of the surface winds at the site. Even over the last decade there have been fatal accidents in the global radiosonde network through careless use of hydrogen gas. Managers of radiosonde stations using hydrogen gas must be aware of the dangers of an explosion and must ensure that all staff are properly informed and trained in the use of hydrogen. It is essential that equipment for generating and storing hydrogen is well maintained. Faulty equipment shall not be used. The balloon filling equipment must be grounded to earth to prevent static discharge.

In strong winds the launching procedure 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 used solely for radiosonde operations. These 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 release. The operator should be aware of inserting surface observations into the ground system prior to launch, as meteorological conditions may change before the launch actually takes place when a significant delay in the launch procedure occurs (for instance, a balloon burst prior to launch, or air traffic control delay). It is particularly important to ensure that the surface pressure measurement inserted into the ground system is accurate if the radiosonde system's pressure measurements are GPS-based.

The speed of response of the radiosonde sensors is such that conditioning the radiosonde before launch is less critical than in the past. However, when it is raining, it will be necessary to provide some protection for the radiosonde sensors prior to launch.

12.7.4 Radiosonde suspension during flight

The radiosonde must not be suspended too close to the balloon when 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 the 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 from 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).

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 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 possible only 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 injury. The parachute must reduce the rate of descent near the surface to less than about 6 m s^{-1}. The remains of the balloon following a 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 a 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. Further considerations on environmentally friendly radiosondes are detailed in Annex 12.C.

12.8 COMPARISON, CALIBRATION AND MAINTENANCE

12.8.1 Comparisons

The overall quality of operational measurements of geopotential height by radiosonde (and hence temperature measurements averaged through thick layers) is monitored at particular forecast centres by comparison to geopotential heights at standard pressures with short-term (6 h) forecasts from global numerical weather prediction models for the same location. The statistics are summarized into monthly averages that are used to identify both substandard measurement quality and significant systematic changes in radiosonde performance. The European Centre for Medium-Range Weather Forecasts, in Reading (United Kingdom), 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 the time series of measurements of geopotential height, at 100 hPa or lower pressures, where atmospheric variability is usually small from day to day. Examples of the compatibility between the results from this method and those from comparison with short-term forecast fields are provided in Nash (1984) and WMO (1989*b*, 1993*b*, 1998, 2003).

Statistics of the performance of the relative humidity sensors are also generated by the numerical weather prediction centres, and are also compared with satellite observations.

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. Annex 12.D gives guidelines for organizing radiosonde intercomparisons and for the establishment of test sites. 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 now be achieved by using measurements taken from two different well-tested GPS radiosondes.

12.8.1.1 Quality evaluation using short-term forecasts

For the better global numerical weather prediction models, the random error in short-term (6 h) 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, 6 h 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. Nonetheless, 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. Reference WMO (2003) provides the most recent reported review of radiosonde errors in the global network for heights up to 30 hPa, and subsequent monitoring statistics can be found on the WMO website at http://www.wmo.int/pages/prog/www/IMOP/monitoring.html.

12.8.1.2 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 change only slowly with time. Suitable pressure levels are 100, 50, or 30 hPa. For radiosonde observations made at 12 h 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 subsequently computed by incrementing in steps of 24 h 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, the sensitivity of this procedure is similar 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 and up to 30 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. The 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.

12.8.1.3 Comparison of water vapour measurements with remote-sensing

Given that many radiosonde stations now have collocated GPS water vapour sensors and some scientific sites have collocated microwave radiometers, it is practical to use the integrated water vapour measurements from these two systems to check the quality of the radiosonde water vapour measurements, primarily at low levels. Comparison with GPS measurements was performed during the last two WMO radiosonde comparisons (WMO, 2006*a*, 2011*b*), where the GPS measurements were used to quantify day–night differences in the radiosonde relative humidity measurements. A more extensive global study was performed by Wang and Zhang (2008). The use of microwave radiometers to check day–night differences is illustrated in Turner et al. (2003).

Although identification of day–night differences with integrated water vapour measurements seems relatively reliable, this does not mean that all the differences seen between radiosonde and remotely sensed water vapour are due to errors in the radiosonde water vapour, since both the GPS water vapour and microwave radiometer measurements have errors that are not necessarily constant with time.

12.8.1.4 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. However, it is important to design the support rig for the radiosondes so that the motion of the radiosondes under the supports is not too dissimilar from the motion on an individual balloon, and to ensure that in daylight the support rig (including the balloon) does not shed warmer air onto some of the sensors from time to time.

Laboratory tests should be performed in facilities similar to those required for the 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.

In order to compare measurements taken during actual ascents, the timing of the samples for the different systems must 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*b*). 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 (i.e., one time of day). Since it is unwise to assume that daytime flights at all solar elevations will have the same bias, it is preferable to organize tests that 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, 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*a*, 2006*a*, 2006*b*, 2006*c*, 2011*b*). The results from these tests were the basis of the information provided in Tables 12.2 and 12.6 to 12.8.

The first international comparison of radiosondes was held at Payerne (Switzerland) in 1950. Average systematic differences between radiosonde pressures and temperatures (at pressures higher than 100 hPa) were 4 hPa and 0.7 K, with random errors (two standard deviations) of 14 hPa and 2 K. These values should be compared with the results for modern systems shown in Tables 12.2 and 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 having a radiation error as large as 10 K.

12.8.2 Calibration

The calibration methods 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, the in-flight failure rate of radiosondes from reliable manufacturers should not be higher than 1 % or 2 %.

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 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 able to cover the range of pressures and temperatures 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% 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 % relative humidity. Reference thermometers should be positioned in the calibration chamber in order to identify the range of temperatures in the space occupied by the sensors under calibration. The range of temperatures should not exceed 0.5 K. Sufficient measurements should be taken to ensure that the calibration curves represent the performance of the sensors to the accuracy required by the users. Pressure sensors which 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 rapidly circulates air past a ventilated psychrometer or dewpoint 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 % are readily obtained. The standard deviation of the variation in relative humidity should not exceed 1 % 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 of which is kept saturated with water while the other is dried by silica gel, with the relative humidity of the mixture being manually controlled by a valve which regulates the relative amounts passing into the duct.

Because of the importance of the type or batch calibration of radiosondes, the Commission for Instruments and Methods of Observation 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.[4]

12.8.3 Maintenance

Failure rates in the ground system should be low for radiosonde systems based on modern electronics, as long as adequate protection is provided against lightning strikes close to the aerials. The manufacturer should be able to advise on a suitable set of spares for the system. A faulty module in the ground system would normally be replaced by a spare module while it is returned to the manufacturer 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 capabilities (both mechanical and electrical). This will be essential if accurate tracking capability is to be retained and if long-term drifts in systematic height errors are to be avoided.

12.9 COMPUTATIONS AND REPORTING

There are no prescribed standardized procedures for the computation of radiosonde observations. The main issue is the selection of levels or the provision of measurements in sufficient detail to reproduce accurately and efficiently the temperature and humidity profile (such as the heights of

[4] As recommended by the Commission for Instruments and Methods of Observation at its eleventh session held in 1994, through Recommendation 9 (CIMO-XI).

temperature inversions) against geopotential from the radiosonde data. Guidance is given in WMO (1986) and in the coding procedures agreed by WMO (2011*c*) (Code FM 35–XI Ext. TEMP). However, the accuracy of this reporting method was suitable for the performance of radiosondes in 1970, but not for today. In order to justify the cost of the radiosonde, it is essential that the radiosonde information be reported more accurately and in more detail than in the TEMP code using relevant BUFR codes. In some cases, the use of BUFR code has involved only retaining the description of the ascent as contained in the TEMP code. This is not the intention of this Guide: a BUFR template should be used allowing a more detailed representation of the vertical structure of the meteorological variables, reported with a resolution that does not generate additional uncertainty in the measurements of these variables.

12.9.1 Radiosonde computations and reporting procedures

Upper-air measurements are usually input into numerical weather forecasts as a series of levels as reported or layer averages, with 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.

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 for temperature and up to ±15 % 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 is possible with manual computations. The manual processing of radiosonde measurements nearly always introduces unnecessary errors in upper-air computations and should be eliminated.

The available algorithms for automated upper-air TEMP 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 reporting 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. Today, the advent of improved meteorological communications should allow the approximation in reporting upper-air observations to be reduced by reporting measurements in detail using the appropriate BUFR code message.

Given the large amount of money spent each year on radiosonde consumables, radiosonde operators should migrate urgently to BUFR (or equivalent) codes, to enable them to report accurately all the information that is measured and is needed by the user community.

12.9.2 Corrections

It should be clear from earlier sections that 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 that achieved with manual systems. It is vital that these algorithms are adequately documented. Users should be informed of any significant improvements or modifications to the algorithms. Records archived in radiosonde stations should include the model numbers of radiosondes in use and an adequate reference to the critical algorithms used for data processing.

All radiosonde temperature measurements have radiation errors. Therefore, it is recommended that a radiation correction (based on expected sensor performance in usual conditions) should always be applied during data processing, if known. 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 these errors are not independent of atmospheric temperature. Thus, it is preferable to eliminate as soon as possible the use of white paint with high emissivity in the infrared as a sensor coating, 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 using 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.

Relative humidity measurements may have corrections applied for slow time-constants of response and for daytime heating of the humidity sensor system. As with temperature, the records of corrections and changes to the correction procedures need to be known by the user and retained in the station archive of observations, preferably along with a raw data archive. The details of these algorithms need to be clear to those purchasing new systems.

Considering the importance of the ways in which corrections are applied, the Commission for Instruments and Methods of Observation[5] urges Members to:

(a) To correct and make available the corrected upper-air data from the various Global Observing System upper-air stations;

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

(c) To 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) To inform WMO of the method of correction applied.

[5] As recommended by the Commission for Instruments and Methods of Observation at its eleventh session, held in 1994, through Recommendation 8 (CIMO-XI).

12.10 PROCUREMENT ISSUES

12.10.1 Use and update of the results from the WMO Intercomparison of High Quality Radiosonde Systems

The results of the WMO Intercomparison of High Quality Radiosonde Systems (WMO, 2011*b*) were published to provide a snapshot in 2010 of the relative performance of the different systems in tropical conditions. The report includes an assessment of the operational performance of the radiosonde systems (see WMO, 2011*b*, Table 12.1). While many of the systems performed well, some radiosondes had limitations in their measurements, mostly in daytime temperature but also in night-time relative humidity measurements at temperatures higher than −40 °C and in daytime relative humidity measurements in the upper troposphere at temperatures lower than −40 °C.

Table 12.1 of the report is intended to help manufacturers identify where the most critical problems lie. Once these deficiencies have been identified, it is probable that many can and will be improved within a year or two, as was done with the MODEM temperature after non-optimum performance at night was observed in the WMO Radiosonde Comparison in Mauritius (WMO, 2006*a*). Therefore, WMO recommends that manufacturers, especially those with markings below 3 in Table 12.1, arrange for a limited number of independent tests to be conducted to provide evidence to WMO that the performance has been improved once the problem has been rectified. Otherwise, manufacturers with promising products may be rejected inappropriately in the procurement process.

WMO (2015b) contains individual radiosonde values for Tables 12.5 to 12.16 from the test in Yangjiang, China, and these can also be used as a guide to the systems with low systematic bias and fast enough time constants of response leading to small sonde error in relative humidity. Low and stable systematic bias is very desirable for radiosonde measurements for climate records.

12.10.2 Some issues to be considered in procurement

The first stage in the procurement process should be to determine what quality of radiosonde is necessary for use in a given network. Here, it is recommended that any radiosonde used should be capable of meeting the breakthrough requirements indicated in Annex 12.A in the climate of that country. If the radiosonde station is considered important for climate records, then a radiosonde performing closer to the optimum requirement should be considered. Ideally the procurement should be competitive. This may mean cooperating with other countries in a similar region to procure larger numbers together and to try and set up a system where the radiosondes are procured on a regular basis, for instance each year or every two years. It should be remembered that systems that differ only slightly in their performance would probably come out in a different order if the tests were repeated. Thus, only marked differences in performance should be treated as significant and not small differences in the relative marking.

Experience from consultations in regional training workshops suggests that there are some issues which need to be considered when procuring equipment:

(a) Equipment must be sustainable over the long term. In other words, in addition to purchasing the hardware and software, arrangements must be made for the long-term support of the system, either by the manufacturer or the local staff, or a mixture of both.

(b) Make sure that the ground antenna is sufficiently sensitive to receive signals under all conditions at the site, whether upper winds are very weak or very strong. Do not try to save money by buying a cheap antenna which is inadequate in some conditions.

(c) Decide whether local staff can maintain a secondary radar and thus use cheaper non-GPS radiosondes, or whether a fully automated GPS radiosonde system is more likely to be successful and run successfully in the long term. Note also that the use of radar-derived wind measurements will result in lower-accuracy wind measurements than those obtained by GPS radiosondes. Therefore, one must also decide whether the reduced wind measurement accuracy is tolerable if opting for non-GPS radiosondes.

(d) If a GPS radiosonde system is to be procured, check whether there is any source of local radio-frequency interference likely to cause problems.

(e) Decide what altitude performance is required and determine which sondes and balloon size will suit (if the radiosondes are not to be used at pressures lower than 30 hPa, then there is a wider range of suitable radiosondes available; see Tables 12.5 to 12.8).

(f) Decide what relative humidity sensor performance is required (for example, a GRUAN or GUAN (GCOS Upper-Air Network) station has a higher standard required than a routine Global Observing System station) basing the requirement on Table 12.1 of WMO (2011*b*) and Tables 12.11 to 12.16 of this Guide.

(g) If conditions are often wet and cloudy, specify that radiosonde sensors need to have some protection against wetting and contamination, and ask for evidence on how this works.

(h) Ask for a compensation agreement if too many radiosondes fail in flight.

(i) Ask for evidence that the manufacturer has reliably supplied radiosondes to other users on the scale that will be used at the station.

(j) Make sure that the ground equipment can produce messages which allow higher resolution data to be reported compared to the old TEMP message. This message must be suitable for the communications available from the site and meet user requirements for data with good vertical resolution.

(k) Ensure that the ground equipment computers are compatible with the local telecommunication system (including internet links, if required).

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ANNEX 12.A. CURRENT BREAKTHROUGH AND OPTIMUM ACCURACY REQUIREMENTS FOR RADIOSONDE MEASUREMENTS

Note: The requirements are based on current technological capability as assessed in the eighth WMO international radiosonde intercomparison, in Yangjiang, China (WMO, 2011*b*). They apply to radiosonde measurements in synoptic and climate meteorology.

TABLE: Table horizontal lines

Variable	*Height (km) (temperature (°C) in the case of humidity)*	*Breakthrough uncertainty requirement*[a,b]	*Optimum uncertainty requirement*[b]
Pressure	1	3 hPa	2 hPa
	10	3 hPa	1 hPa
	16	2 hPa	0.6 hPa

	24	1 hPa	0.2 hPa
	32	0.4 hPa	0.1 hPa
Temperature	0 to 16	1 K	0.4 K
	Above 16	2 K	0.8 K
Relative humidity	0 to 12 (40 °C to –50 °C)[c]	15 % RH	6 % RH
(Troposphere only)	12 to 17 (–50 °C to –90 °C)[c]	30 % RH	10 % RH
Mixing ratio, lower stratosphere (specialized systems)	12 to 25	20 % ppmv[d]	4 % ppmv
Wind direction	0 to 16	10°, speed < 10 m s^{-1} 4° at higher speeds	5°, speed < 10 m s^{-1} 2° at higher speeds
	Above 16	20°, speed < 10 m s^{-1} 8° at higher speeds	5°, speed < 10 m s^{-1} 2° at higher speeds
Wind speed	0 to 16	2 m s^{-1}	1 m s^{-1}
	Above 16	4 m s^{-1}	1 m s^{-1}
Wind components	0 to 16	2 m s^{-1}	1 m s^{-1}
	Above 16	3 m s^{-1}	1 m s^{-1}
Geopotential height of significant level	1	30 gpm	20 gpm
	5	40 gpm	20 gpm
	10	60 gpm	20 gpm
	16	120 gpm	40 gpm
	20	200 gpm	40 gpm
	32	240 gpm	60 gpm

Notes:

a Values derived for the main targeted applications for radiosondes.

b Expressed as expanded uncertainties (k = 2), which encompass approximately 95 % of the variation of results in sounding conditions including all significant sources of uncertainty (e.g. dynamic and radiative conditions).

c Change in expected relative humidity sensor performance corresponds better with temperature than with altitude in the troposphere.

d ppmv = parts per million by volume

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ANNEX 12.B. ESTIMATES OF GOAL, BREAKTHROUGH AND THRESHOLD LIMITS FOR UPPER WIND, UPPER-AIR TEMPERATURE, RELATIVE HUMIDITY AND GEOPOTENTIAL HEIGHT (DERIVED FROM THE WMO ROLLING REVIEW OF REQUIREMENTS FOR UPPER-AIR OBSERVATIONS)

(a) The *goal* is an ideal requirement above which further improvements are not necessary.

(b) The *breakthrough* is an intermediate level between *threshold* and *goal* which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems.

(c) The *threshold* is the minimum requirement to be met to ensure that data are useful.

It is recommended that expenditure on radiosondes be considered as justified when the accuracy and vertical resolution obtained is equal to or better than the threshold and as close to the goal as is affordable.

Table 12.B.1. Summary of WMO/GCOS limits for uncertainty (root-mean-square vector error, k = 2) and vertical resolution for upper wind measurements

TABLE: Table horizontal lines

Layer		*Goal for NWP*	*Goal for climate*	*Breakthrough for NWP*	*Breakthrough for climate*	*Threshold for NWP*	*Threshold for climate*
Lower troposphere	Uncertainty	1[a] – 2 m s^{-1}	1.4[b] – 4[c] m s^{-1}	4 m s^{-1}	6 m s^{-1}	10 m s^{-1}	10 m s^{-1}
Lower troposphere	Vertical resolution	200 m	50[b] – 500[c] m	300 m	800 m	500 m	2 km
Upper troposphere	Uncertainty	1[b] – 2[c] m s^{-1}	1.4[b] – 4[c] m s^{-1}	4 m s^{-1}	6 m s^{-1}	10 m s^{-1}	10 m s^{-1}
Upper troposphere	Vertical resolution	500 m	50[b] – 500[c] m	700 m	800 m	1 km	2 km
Lower stratosphere	Uncertainty	2 m s^{-1}	1.4[b] – 4[c] m s^{-1}	4 m s^{-1}	6 m s^{-1}	10 m s^{-1}	10 m s^{-1}
Lower stratosphere	Vertical resolution	1 km	250[b] – 500[c] m	2 km	800 m	3 km	2 km
Upper stratosphere	Uncertainty	2 m s^{-1}	1.4[b] – 4[c] m s^{-1}	6 m s^{-1}	8 m s^{-1}	16 m s^{-1}	10 m s^{-1}

Upper stratosphere	Vertical resolution	1 km	250[b] – 500[c] m	2 km	800 m	3 km	2 km
Long-term stability			0.1 m s^{-1} in 10 years				

Notes:

a Limit derived from atmospheric variability studies (WMO, 1970).

b Limit derived from the GCOS Reference Upper-Air Network observation requirements (WMO, 2009).

c Limit derived from the Commission for Basic Systems (CBS) Rolling Review of Requirements WMO observing requirements database (OSCAR/Requirements; see WMO, 2014), sampled August 2011.

Table 12.B.2. Summary of WMO/GCOS uncertainty (k = 2) and vertical resolution limits for upper-air temperature measurements (Note: These limits are for temperatures at a given height and may be different to those when temperatures are integrated over relatively deep layers, e.g. see Table 12.B.4 for breakthrough limits derived from requirements for 100 hPa geopotential height.)

TABLE: Table horizontal lines

Layer		*Goal for NWP*	*Goal for climate*	*Breakthrough for NWP*	*Breakthrough for climate*	*Threshold for NWP*	*Threshold for climate*
Lower troposphere	Uncertainty	0.6[a] – 1[c] K	0.2[b] – 1[c] K	1.8 K	1.2 K	6[c] K (extratropics) 3[a] K (tropics)	2 K
Lower troposphere	Vertical resolution	100 m	100 m	200 m	800 m	1 km	2 km
Upper troposphere	Uncertainty	0.6[a] – 1[c] K	0.2[b] – 1[c] K	1.8 K	1.2 K	6[c] K (extratropics) 3[a] K (tropics)	2 K
Upper troposphere	Vertical resolution	300 m	100 m	400 m	800 m	1 km	2 km
Lower stratosphere	Uncertainty	1[c] K	0.4[b] – 1[c] K	1.8 K	1.2 K	6[c] K (extratropics) 3[a] K (tropics)	2 K
Lower stratosphere	Vertical resolution	1 km	100[b] – 500[c] m	1.5 km	800 m	3 km	2 km
Upper stratosphere	Uncertainty	1[c] K	0.4[b] – 1[c] K	2.8 K	1.2 K	6 K	2 K

Upper stratosphere	Vertical resolution	1 km	100[b] – 500[c] m	1.5 km	800 m	3 km	2 km
Long-term stability			0.05 K in 10 years[b]				

Notes:

a Limit derived from atmospheric variability studies (WMO, 1970).

b Limit derived from the GCOS Reference Upper-Air Network observation requirements (WMO, 2009).

c Limit derived from the CBS Rolling Review of Requirements WMO observing requirements database (OSCAR/Requirements; see WMO, 2014), sampled August 2011.

Table 12.B.3. Summary of WMO/GCOS performance limits for aerological instruments measuring humidity

TABLE: Table horizontal lines

Layer		*Goal for NWP*	*Goal for climate*	*Breakthrough for NWP*	*Breakthrough for climate*	*Threshold for NWP*	*Threshold for climate*
Lower troposphere	Uncertainty	2[a] – 4[c] % RH	4 % RH	16 % RH	6 % RH	40 % RH	10 % RH
Lower troposphere	Vertical resolution	100 m	50[b] – 500[c] m	200 m	800 m	1 km	2 km
Upper troposphere	Uncertainty	4 % RH	4 % RH	16 % RH	6 % RH	40 % RH	10 % RH
Upper troposphere	Vertical resolution	300 m	100[b] – 500[c] m	500 m	800 m	1 km	2 km
Lower stratosphere	Uncertainty	10 % mixing ratio ppmv	4 % mixing ratio ppmv	16 % mixing ratio ppmv	6 % mixing ratio ppmv	40 % mixing ratio ppmv	10 % mixing ratio ppmv
Lower stratosphere	Vertical resolution	1 km	100[b] – 500[c] m	1.5 km	800 m	3 km	2 km
Upper stratosphere	Uncertainty	Not stated	4 % mixing ratio ppmv	Not stated	6 % mixing ratio ppmv	Not stated	10 % mixing ratio ppmv
Upper stratosphere	Vertical resolution	Not stated	100[b] – 500[c] m	Not stated	800 m	Not stated	2 km
Long-term			0.3 % in				

stability	10 years[b]

Notes:

a Limit derived from atmospheric variability studies (WMO, 1970).

b Limit derived from the GCOS Reference Upper-Air Network observation requirements (WMO, 2009).

c Limit derived from the CBS Rolling Review of Requirements WMO observing requirements database (OSCAR/Requirements; see WMO, 2014), sampled August 2011.

Note: The Rolling Requirement and GCOS requirement refer to specific humidity, but this leads to far too stringent limits on uncertainty in layers where relative humidity is very low in the lower and middle troposphere. So values are shown as approximately equivalent relative humidity, and mixing ratio should be used at very low temperatures or in the stratosphere.

Table 12.B.4. Summary of uncertainty (k = 2) and vertical resolution limits for geopotential heights of 100 hPa and significant levels, consistent with WMO/GCOS limits for upper-air temperature

TABLE: Table horizontal lines

Layer		*Goal for NWP*	*Goal for climate*	*Breakthrough for NWP*
Surface to 100 hPa	Uncertainty	24 gpm (= to 0.4 K temperature layer)	12 gpm (= to 0.2 K temperature layer)	50 gpm (= to 0.8 K temperature layer)
Lower troposphere	Uncertainty for temperature[a]	40 gpm	16 gpm on average	120 gpm
Lower troposphere	Uncertainty for cloud base[b]	30 gpm		
Upper troposphere	Uncertainty for temperature[a]	40 gpm	14 gpm on average	120 gpm
Lower stratosphere equatorial	Uncertainty for temperature[a]	70 gpm	48 gpm	200 gpm
Lower stratosphere extratropical	Uncertainty for temperature[a]	100 gpm	68 gpm	300 gpm
Upper stratosphere	Uncertainty for temperature[a]	80 gpm	60 gpm	240 gpm
Long-term stability			4 – 8 gpm in 10 years	

Notes:

a Limit for height error produces a typical temperature error of half the magnitude specified for the limits for temperature in Table 12.B.2.

b Limit derived to be compatible with measurements from operational laser ceilometers in the lower troposphere.

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ANNEX 12.C. ENVIRONMENTALLY FRIENDLY RADIOSONDES

About 620 000 radiosondes are launched worldwide annually. After launch the radiosonde ascends through the atmosphere until the balloon bursts and the radiosonde falls to the earth. All radiosondes with balloon segments and flight train fall to the ground or in the ocean, and thus create environmental pollution.

Balloon-borne waste has the ability to reach very remote areas and is often the only source of human-made waste in inland wilderness areas, wildlife sanctuaries and other environmentally sensitive areas.

Flight trains pose a particular environmental issue. They often cause the radiosonde payload to get caught in trees, power lines and towers, or to float in the oceans where it can remain for years. Flight trains present a long-term entanglement threat to wildlife on land and in the oceans.

The main difficulty in producing environmentally friendly radiosondes is identifying materials that both meet the functional requirements and are biodegradable. Most current radiosonde parts are made from non-biodegradable materials. There are biodegradable plastics, but currently only one radiosonde manufacturer has showcased a radiosonde housing made from such materials. Other manufacturers are encouraged to use biodegradable plastics or other suitable materials for radiosondes.

Radiosondes vary in size and weight. As the larger heavier radiosondes descend they pose a threat to people and animals. Current technologies allow the manufacture of smaller and lighter radiosondes. All manufacturers are encouraged to reduce the size and weight of their radiosondes while maintaining functionality. An advantage of lighter radiosondes is that they can use a smaller balloon therefore requiring less gas. The reduced size of the balloon also means less polluting materials.

Flight trains are often made of non-biodegradable cord, such as nylon, which can persist in the environment for decades. Switching flight train material to a biodegradable cordage, such as cotton twine, or polypropylene without UV protection, is recommended. This will reduce the entanglement risk to wildlife in the oceans and on land, and will result in the more rapid release of radiosonde payloads caught in trees, powerlines and other structures.

Synthetic latex balloons have a much slower rate of decomposition than natural rubber latex, therefore balloons made of natural rubber latex are preferred.

Radiosonde batteries of all types, for example alkaline, lithium and water-activated batteries, contain toxic and corrosive chemicals. There are currently no environmentally friendly batteries, however lithium batteries present lower impacts. As manufacturers reduce the power consumption of radiosondes this will allow for smaller batteries and a further reduction in the overall waste

Operators and manufacturers of radiosondes should encourage the collection and return, or the disposal of radiosondes according to the local regulations for the treatment of electronic and chemical waste. The balloon and flight train should be disposed of as normal waste. Local treatment minimizes any additional environmental footprint related to transport of the used radiosondes.

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ANNEX 12.D. GUIDELINES FOR ORGANIZING RADIOSONDE INTERCOMPARISONS AND FOR THE ESTABLISHMENT OF TEST SITES[6]

PART I – GUIDELINES FOR ORGANIZING RADIOSONDE INTERCOMPARISONS

1. Introduction

1.1 These guidelines assume that procedures that may be established by various test facilities are consistent with procedures established by other national and international organizations. They also assume that an Organizing Committee will be formed of participants (Members) interested in comparing radiosondes and that at least one non-participant will be included with ability to provide guidance for conducting the intercomparison. The involvement of an independent non-participant is important in order to avoid bias during the planning of the intercomparison. Consideration must also be given to whether radiosonde manufacturers' personnel should actively participate or whether independent operational personnel of the host should prepare and launch such radiosondes.

1.2 All intercomparisons differ from each other to some extent; therefore, these guidelines are to be construed only as a generalized checklist of tasks needing to be accomplished. Modifications should be made by the Organizing Committee, as required, but the validity of the results and scientific evaluation should not be compromised.

1.3 Final reports of previous intercomparisons and organizational meeting reports of other Organizing Committees may serve as an example of the methods that can be adopted for the intercomparison. These previous reports should be maintained and made available by the WMO Secretariat.

2. Objectives of intercomparisons

2.1 The intercomparison objectives must be clear, must list what is expected from the intercomparisons and identify how results will be disseminated. The Organizing Committee is tasked to examine the achievements to be expected from the radiosonde intercomparison and to identify and anticipate any potential problem. The Organizing Committee's role is to provide guidance, but it must also prepare clear and detailed statements of the main objectives and agree on the criteria to be used in evaluating the results. The Organizing Committee should also determine how best to guarantee the success of the intercomparison by drawing on background knowledge and accumulated experience from previous intercomparisons.

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[6] Based on the *Abridged Final Report with Resolutions and Recommendations of the Twelfth Session of the Commission for Instruments and Methods of Observation* (WMO-No. 881), Annex II, and updated thereafter.

3. Place, date and duration of intercomparison

3.1 The host facility should provide to the Organizing Committee and to the participants a description of the proposed intercomparison site and facilities (locations, etc.), environmental and climatological conditions, and site topography. The host facility should also name a Project Leader or Project Manager who will be responsible for the day-to-day operation and act as the facility point of contact.

3.2 The Organizing Committee should visit the proposed site to determine the suitability of its facilities and to propose changes, as necessary. After the Organizing Committee agrees that the site and facilities are adequate, a site and environmental description should be prepared by the Project Leader for distribution to the participants. The Project Leader, who is familiar with his facility's schedule, must decide the date for the start of the intercomparison, as well as its duration. A copy of this schedule shall be delivered to the Organizing Committee.

3.3 In addition to the starting date of the intercomparisons, the Project Leader should propose a date when his facility will be available for the installation of the participant's equipment and arrange for connections to the data acquisition system. Time should be allowed for all of the participants to check and test equipment prior to starting the intercomparison and to allow additional time to familiarize the operators with the procedures of the host facility.

4. Participation

4.1 As required, the Project Leader and/or Organizing Committee should invite, through the Secretary-General of WMO, participation of Members. However, once participants are identified, the Project Leader should handle all further contacts.

4.2 The Project Leader should draft a detailed questionnaire to be sent by the Secretary-General to each participant in order to obtain information on each instrument type proposed to be intercompared. Participants are expected to provide information on their space, communication, unique hardware connection requirements, and software characteristics. They also should provide adequate documentation describing their ground and balloon-borne instrumentation.

4.3 It is important that participants provide information about their radiosonde calibration procedures against recognized standards. Although it is expected that operational radiosondes will be intercompared, this may not always be the case; new or research-type radiosondes may be considered for participation with the agreement of all of the participants, the Project Leader, and the Organizing Committee.

5. Responsibilities

5.1 Participants

5.1.1 The participants shall be responsible for the transportation of their own equipment and costs associated with this transportation.

5.1.2 The participants should install and remove their own equipment with the cognizance of the Project Leader. The host facility shall assist with unpacking and packing, as appropriate.

5.1.3 The participants shall provide all necessary accessories, mounting hardware for ground equipment, signal and power cables, spare parts and expendables unique to their system. The participants shall have available (in the event that assistance from the host facility should become necessary) detailed instructions and manuals needed for equipment installation, operation, maintenance and, if applicable, calibration.

5.1.4 The participants should sign the data protocol agreement of the intercomparison.

5.2 Host facility

5.2.1 The host facility should assist participants in the unpacking and installation of equipment as necessary, and provide storage capability to house items such as expendables, spare parts and manuals.

5.2.2 The host facility should provide auxiliary equipment as necessary, if available.

5.2.3 The host facility should assist the participants with connections to the host facility's data acquisition equipment, as necessary.

5.2.4 The host shall insure that all legal obligations relating to upper-air measurements (for example, the host country's aviation regulations and frequency utilization) are properly met.

5.2.5 The host facility may provide information on items such as accommodation, local transportation and daily logistics support, but is not obligated to subsidize costs associated with personnel accommodation.

6. Rules during the intercomparison

6.1 The Project Leader shall exercise control of all tests and will keep a record of each balloon launch, together with all the relevant information on the radiosondes used in the flight and the weather conditions.

6.2 Changes in equipment or software will be permitted with the cognizance and concurrence of the Project Leader. Notification to the other participants is necessary. The Project Leader shall maintain a log containing a record of all the equipment participating in the comparison and any changes that occur.

6.3 Minor repairs (for example, fuse replacement, etc.) not affecting instrumentation performance are allowed. The Project Leader should be made aware of these minor repairs and also submit the information to the record log.

6.4 Calibration checks and equipment servicing by participants requiring a specialist or specific equipment will be permitted after notification to the Project Leader.

6.5 Any problem that compromises the intercomparison results or the performance of any equipment shall be addressed by the Project Leader.

7. Data acquisition

7.1 The Organizing Committee should agree on appropriate data acquisition procedures such as measurement frequency, sampling intervals, data averaging, data reduction (this may be limited to an individual participant's capability), data formats, real-time quality control, post-analysis quality control and data reports.

7.2 The initial international Organizing Committee shall decide on the data acquisition hardware and software for the test. This should be well tested before commencement of the intercomparison, and the use of an established processing package such as described in WMO (1996*b*) is to be preferred.

7.3 The time delay between observation and delivery of data to the Project Leader shall be established by the Project Leader and agreed by the participants. One hour after the end of the observation (balloon burst) should be considered adequate.

7.4 The responsibility for checking data prior to analysis, the quality control steps to follow, and delivery of the final data rests with the Project Leader.

7.5 Data storage media shall be the Project Leader's decision after taking into consideration the capability of the host facility, but the media used to return final test data to participants may vary in accordance with each of the participant's computer ability. The Project Leader should be cognizant of these requirements.

7.6 The Project Leader has responsibility for providing final data to all participants and, therefore, the host facility must be able to receive all individual data files from each participant.

8. Data processing and analysis

8.1 Data analysis

8.1.1 A framework for data analysis should be encouraged and decided upon even prior to beginning the actual intercomparison. This framework should be included as part of the experimental plan.

8.1.2 There must be agreement among the participants as to methods of data conversion, calibration and correction algorithms, terms and abbreviations, constants, and a comprehensive description of proposed statistical analysis methods. It is essential that the data processing be performed by experienced experts, nominated by WMO.

8.1.3 The Organizing Committee should verify the appropriateness of the analysis procedures selected.

8.1.4 The results of the intercomparisons should be reviewed by the Organizing Committee, who should consider the contents and recommendations given in the final report.

8.2 Data processing and database availability

8.2.1 All essential meteorological and environmental data shall be stored in a database for further use and analysis by the participants. The Project Leader shall exercise control of these data.

8.2.2 After completion of the intercomparison, the Project Leader shall provide a complete set of all of the participants' data to each participant.

9. Final report of the intercomparison

9.1 The Project Leader shall prepare the draft final report which shall be submitted to the Organizing Committee and to the participating members for their comments and amendments. A time limit for reply should be specified.

9.2 Comments and amendments should be returned to the Project Leader with copies also going to the Organizing Committee.

9.3 When the amended draft final report is ready, it should be submitted to the Organizing Committee, who may wish to meet for discussions, if necessary, or who may agree to the final document.

9.4 After the Organizing Committee approves the final document for publication, it should be sent to the Secretariat for publication and distribution by WMO.

9.5 Reproduction for commercial purposes of any plots or tables from the final report should not be allowed without specific permission from WMO.

10. Final comments

10.1 The Organizing Committee may agree that intermediate results may be presented only by the Project Leader, and that participants may present limited data at technical conferences, except that their own test data may be used without limitation. Once the WMO Secretariat has scheduled the final report for publication, WMO shall make the data available to all Members who request them. The Members are then free to analyse the data and present the results at meetings and in publications.

PART II – GUIDELINES FOR THE ESTABLISHMENT OF TEST SITES

1. Introduction

1.1 In order to support the long-term stability of the global upper-air observing system, it is essential to retain the capability of performing quantitative radiosonde comparisons. Current and new operational radiosonde systems must be checked against references during flight on a regular basis. Members must ensure that a minimum number of test sites with the necessary infrastructure for performing radiosonde comparison tests are retained.

1.2 Experience with the series of WMO Radiosonde Intercomparisons since 1984 has shown that it is necessary to have a range of sites in order to compare the radiosondes over a variety of flight conditions.

1.3 Relative humidity sensor performance is particularly dependent on the conditions during a test, for example, the amount of cloud and rain encountered during ascents, or whether surface humidity is high or low.

1.4 Daytime temperature errors depend on the solar albedo, and hence the surface albedo and cloud cover. Thus, temperature errors found at coastal sites may differ significantly from continental sites. Infrared errors on temperature sensors will not only depend on surface conditions and cloud distribution, but also on atmospheric temperature. Thus, infrared temperature errors in the tropics (for instance near the tropopause) will be quite different from those at mid-latitudes.

1.5 The errors of many upper-wind observing systems depend on the distance the balloon travels from the launch site (and also the elevation of the balloon from the launch site). Thus, comparison tests must cover situations with weak upper winds and also strong upper winds.

2. Facilities required at locations

2.1 Locations suitable for testing should have enough buildings/office space to provide work areas to support the operations of at least four different systems.

2.2 The site should have good quality surface measurements of temperature, relative humidity, pressure and wind, measured near the radiosonde launch sites. Additional reference quality measurements of temperature, pressure and relative humidity would be beneficial.

2.3 The test site should have a method of providing absolute measurements of geopotential height during test flights (probably using a Global Positioning System (GPS) radiosonde capable of producing accurate heights).

2.4 The test site should have a well-established surface-based GPS sensor for measuring integrated water vapour, or ground-based radiometers and interferometers.

2.5 Cloud observing systems at the test site, such as laser ceilometers and cloud radars, are desirable.

2.6 Aerosol lidars and relative humidity lidars may also prove useful at the test site.

2.7 The site must be cleared by the national air traffic control authorities for launching larger balloons (3 000 g) with payloads of up to 5 kg. Balloon sheds must be able to cope with launching these large balloons.

3. Suggested geographical locations

3.1 In order to facilitate testing by the main manufacturers, it is suggested that test sites should be retained or established in mid-latitudes in North America, Europe and Asia. Ideally, each of these regions would have a minimum of two sites, one representing coastal (marine) conditions, and another representing conditions in a mid-continent location.

3.2 In addition, it is suggested that a minimum of two test locations should be identified in tropical locations, particularly for tests of relative humidity sensors.

3.3 If the main test sites noted above do not provide adequate samples of extreme conditions for relative humidity sensors (for example, very dry low-level conditions), it may be necessary to identify further test sites in an arid area, or where surface temperatures are very cold (below −30 °C in winter). It is possible that some of these could be selected from established GRUAN sites.

PART III – GUIDELINES FOR PROTOTYPE TESTING

1. Introduction

1.1 The major WMO radiosonde comparisons are organized about every 5 to 6 years, when a large group of manufacturers can benefit from a large-scale test, with systems that have already been through prototype testing. For new designs or for those manufacturers rectifying problems identified in the WMO radiosonde comparisons, there is a need to perform smaller, less expensive tests.

1.2 It is probably best for manufacturers trying to demonstrate that a problem has been resolved to have the tests done at one of the designated CIMO test sites.

1.3 On the other hand, the development and selection of new national radiosonde designs merits prototype testing at suitable national locations.

2. Recommended procedures

2.1 Testing to prove that problems have been rectified needs to be done to similar standards and methods used in the WMO radiosonde comparisons. This requires that any CIMO test site must have staff who are fully conversant with the procedures and techniques of the WMO radiosonde comparisons, and also requires the use of two radiosonde types of known good quality as working references/link radiosondes to the WMO radiosonde comparison results.

2.2 With national prototype testing it is essential to compare measurements with radiosondes flown together under one balloon. Ideally the radiosondes should be suspended in such a way that they are free to rotate in flight, as this is what happens on individual ascents. The radio-frequency performance of the new radiosonde needs to be good enough to ensure that the frequency does not drift and cause interference to the radiosonde with which it is being compared. Comparison of results should be performed as a function of time into flight, since it is unwise to assume that height/pressure assignments to temperature and relative humidity measurements have negligible errors. The number of initial test flights may be quite small since some initial errors are often large and can be quickly identified even by comparison with a lower quality national radiosonde.

2.3 However, once the aim is to improve the new national radiosonde design so that its measurement quality comes close to that of the high-quality radiosondes tested in the WMO Intercomparison of High Quality Radiosonde Systems, then it will be necessary to use one of the better quality radiosondes as a test reference. Always follow the manufacturer's instructions when preparing the better quality radiosonde for the test flights. Testing must be performed both day and night, since the sonde errors for daytime temperatures need to be identified and at night the errors in relative humidity are often worse than in daytime.

2.4 Final prototype tests need to be performed at a time of year when the variation of relative humidity in the vertical and with time is high at all levels in the troposphere.

3. Archiving of results

3.1 Results of tests at CIMO test centres need to be forwarded to the relevant CIMO expert team for checking and display on the CIMO websites.

3.2 Once a new national development becomes mature, it would also be helpful for the future to forward comparison test results to the relevant CIMO expert team.

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