CHAPTER CONTENTS

CHAPTER 13. MEASUREMENT OF UPPER WIND

13.1 GENERAL

13.1.1 Definitions

The following definitions are taken from the *Manual on the Global Observing System* (WMO, 2010):

Pilot-balloon observation: A determination of upper winds by optical tracking of a free balloon.

Radiowind observation: A determination of upper winds by tracking of a free balloon by electronic means.

Rawinsonde observation: A combined radiosonde and radiowind observation.

Upper-air observation: A meteorological observation made in the free atmosphere either directly or indirectly.

Upper-wind observation: An observation at a given height or the result of a complete sounding of wind direction and speed in the atmosphere.

This chapter will deal primarily with radiowind and pilot-balloon observations. Balloon techniques, and measurements using special platforms, specialized equipment, or made indirectly by remote-sensing methods are discussed in various chapters of Part II. Large numbers of observations are now received from commercial aircraft and also from wind profiler and weather radars. Data from balloons are mainly acquired by using rawinsonde techniques, although pilot-balloon and radiowind observations may be used when additional upper wind data are required without the expense of launching a radiosonde.

13.1.2 Units of measurement of upper wind

The speed of upper winds is usually reported in metres per second or knots, but kilometres per hour are also used. The direction from which the airflow arrives is reported in degrees from north: 90° represents a wind arriving from the east, 180° from the south, 270° from the west and 0/360° from the north. In TEMP reports, the wind direction is rounded to the nearest 5°. Reporting to this resolution degrades the accuracy achievable by the best modern windfinding systems, particularly when upper winds are strong. Data from these systems encoded in BUFR provide more accurate information on the direction and speed of upper wind.

Within 1° latitude of the North or South Pole, surface winds are reported using a direction where the azimuth ring is aligned with its zero coinciding with the Greenwich 0° meridian. This different coordinate system should be used by all fixed and mobile upper-air stations located within 1° latitude of the North or South Pole for wind direction at all levels of the entire sounding, even if the balloon moves farther away than 1° latitude from the pole. The reporting code for these measurements should indicate that a different coordinate system is being used in this upper-air report, in particular if encoded in traditional alphanumeric codes; the location of the station in BUFR automatically indicates usage of this different coordinate system.

The height used in reporting radiowind/rawinsonde measurements is geopotential height so that the wind measurements are at the same heights as the radiosonde measurements of temperature and relative humidity (see Part I, Chapter 12, 12.3.6). The conversion from geometric height, as measured with a GPS radiosonde or radar, 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) of a unit mass of anything is the integral of the normal gravity from mean sea level ($z_{\text{geometric}} = 0$) to the height of the mass ($z_{\text{geometric}} = Z$), as given by equation 13.1.

$$\Phi = \int_0^z \gamma(z_{geometric}, \varphi) dz_{geometric} \tag{13.1}$$

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

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

$$z\left(z_{geometric}, \varphi\right) = \Phi\left(z_{geometric}, \varphi\right) / \gamma_{45°} = \left(\int_0^z \gamma\left(z_{geometric}, \varphi\right) dz_{geometric}\right) / \gamma_{45°} \tag{13.2}$$

where $\gamma_{45°}$ was taken in the definition as 9.806 65 m s^{-2} .

Thus, the unit of height is the standard geopotential metre. In the troposphere, the value of geopotential height is a close approximation to the geometric height expressed in metres (see, for example, Part I, Chapter 12, Table 12.4). The geopotential heights used in upper-wind reports are reckoned from sea level, although in many systems the computations of geopotential height will initially be performed in terms of height above the station level.

The conversion of geometric height to geopotential height is derived in fuller detail in Part I, Chapter 12, with suitable expressions given for the dependence of the gravitational field on height and latitude.

13.1.3 Meteorological requirements

13.1.3.1 *Uses in meteorological operations*

Observations of upper winds are essential for operational weather forecasting on all scales globally, and are often most effective when used in conjunction with simultaneous measurements of mass field (temperature and relative humidity).

(a) In the boundary layer, upper winds providing reliable measurements of vertical wind shear are essential for environmental pollution forecasting;

(b) They are vital to the safety and economy of aircraft operations;

(c) Accurate upper wind and vertical wind shear measurements are critical for the launching of space vehicles and other types of rocket;

(d) Uncertainties in upper winds are the limiting factor in the accuracy of modern artillery, and reliable wind measurements are therefore important for safety in military operations;

(e) Upper winds are one of the essential climate variables.

13.1.3.2 *Improvements in reporting procedures*

Upper winds are normally input into numerical weather forecasts as layer averages, the thickness of the layers depending on the scales of atmospheric motion relevant to the forecast. The values are not usually input at standard pressures or heights, but will usually be centred at pressure heights that vary as the surface pressure changes at the location of the observation. Thus, it is of primary importance that the variation in winds between standard levels is accurately represented in upper-wind reports. This is in addition to ensuring that accurate winds are reported at the standard levels.

In modern radiowind systems, computers have the capability of readily providing all the detailed structure relevant to meteorological operations and scientific research. The upper-wind reports should contain enough information to define the vertical wind shear across the boundaries between the various layers in the mass fields. For instance, wind shear across temperature inversions or significant wind shear associated with large changes in relative humidity in the vertical should be reported whenever possible.

When upper winds are reported using either the FM 35–XI Ext. TEMP code or the FM 32–XI Ext. PILOT code (WMO, 2011*a*), wind speeds are allowed to deviate by as much as 5 m s^{-1} from the linear interpolation between significant levels. The use of automated algorithms with this fitting limit can produce errors in reported messages which are much larger than the observational errors. On occasion, the coding procedure may also degrade the accuracy outside the accuracy requirements outlined in Part I, Chapter 12.

This should be prevented, as soon as possible, by submitting reports in a suitable BUFR code that allows reporting of high-resolution vertical wind data in addition to the significant levels to fulfil user requirements. However, until this is achieved, a fitting limit for a wind speed of 3 m s^{-1} instead of 5 m s^{-1} can be implemented as a national practice for TEMP and PILOT messages. The tightening of the fitting limit should lead, on average, to about one significant level wind report per kilometre in the vertical. The TEMP or PILOT report should be visually checked against the detailed upper-wind measurement, and the reported messages should be edited to eliminate unacceptable fitting errors before issue.

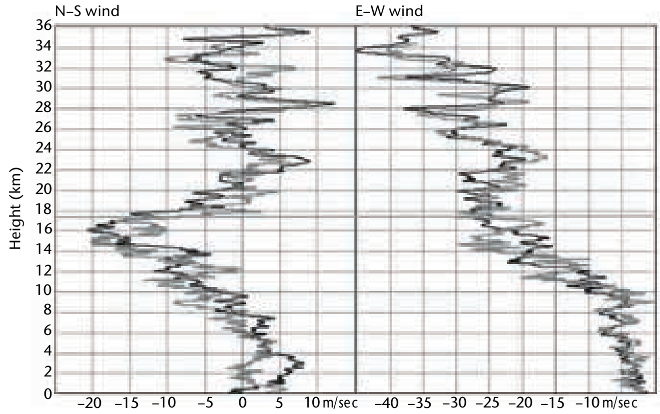
In earlier years, upper winds were generally processed manually or with a small calculator, and it was impractical to produce detailed reports of the vertical wind structure – hence the use of significant levels and the relatively crude fitting limits, which are not appropriate for the quality of observation produced by modern rawinsonde systems.

13.1.3.3 ***Accuracy requirements***

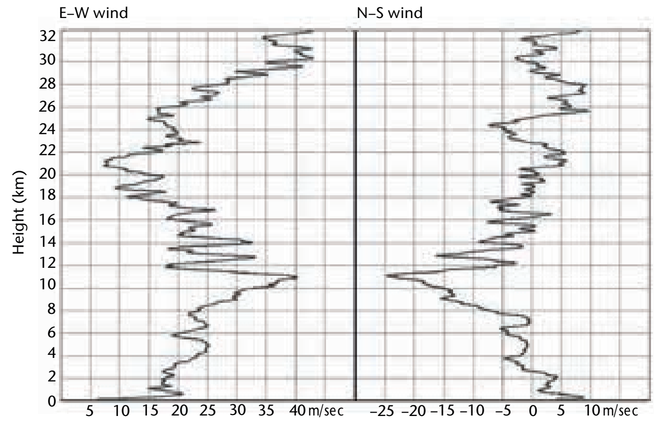
Accuracy requirements for upper-wind measurements are presented in terms of wind speed and direction and also orthogonal wind components in Part I, Chapter 12, Annex 12.A. Most upper-wind systems should be capable of measuring winds over a range from 0 to 100 m s^{-1}. If systems are designed to provide winds at low levels, they may not need to cope with such a large range. Systematic errors in wind direction must be kept as small as possible and certainly much less than 5°, especially at locations where upper winds are usually strong. In the 1990s, most well-maintained operational windfinding systems provided upper winds with a standard vector error (2σ) that was better than or equal to 3 m s^{-1} in the lower troposphere and 5 to 6 m s^{-1} in the upper troposphere and stratosphere (Nash, 1994). The advent of very reliable GPS windfinding systems means that many modern systems are capable of even better performance than this, with a standard vector error ($k = 2$) less than 1 m s^{-1} with little degradation of the measurement quality in the vertical (see the results of the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*)).

Examples of vertical profiles of horizontal wind from Yangjiang, China, and the United Kingdom are shown in Figure 13.1. These measurements were made with a vertical resolution better than 150 m. Figure 13.1(a) shows two measurements from Yangjiang spaced six hours apart. The fine structure in the vertical is not the result of noise, but is the real structure in the atmosphere also measured by the other rawinsonde systems on the respective flights. During this test, there were very strong easterly winds at upper levels in the stratosphere (associated with the easterly phase of the quasi-biennial oscillation). The stronger northerly winds associated with the jet at about 16 km extend up to about 21 km and thus through the tropopause at 17.5 km. The detailed wind structure in the stratosphere between 22 and 34 km mostly persists over seven hours, illustrating that much of the detailed structure is not transient and thus merits archiving and reporting.

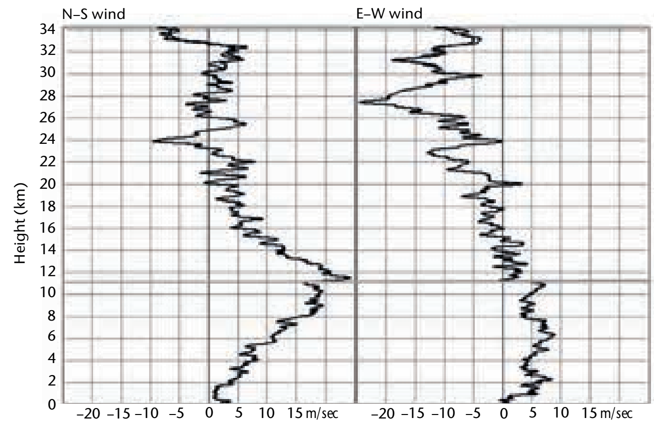
Figure 13.1(b) is from early winter in the United Kingdom, with the tropopause much lower at about 11 km, but again the stronger winds associated with the upper troposphere jet extend up to at least 16 km. The large perturbations in wind caused by the gravity waves immediately above the tropopause would not be resolved at 1 km vertical resolution. On this occasion, there is another jet associated with circulation around the polar vortex at heights above 30 km. Figure 13.1(c) is from UK summertime conditions. In this case there is significant wind shear



(a) Flight 1 at 0800 hours (black) and flight 3 at 1448 hours (grey) on 14 July 2010, from the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China



(b) November measurement made at Camborne, United Kingdom; data from two different radiosonde types are superimposed. (Note: In this frame, the zonal and meridional wind components are reversed, i.e. the zonal component is displayed on the left.)



(c) July measurement made at Camborne, United Kingdom; data from two different radiosonde types are superimposed.

Figure 13.1. Examples of vertical profiles of horizontal wind measured at about 150 m vertical resolution in Yangjiang, China, and in early winter and summer in the United Kingdom; horizontal grey line shows tropopause height.

across the tropopause. Easterly winds predominate in the stratosphere above about 16 km, and these are not as strong as the westerly winds in the winter. However, between 20 and 32 km, there are again significant perturbations in the winds in summertime.

Thus, although the user requirement for vertical resolution quoted for upper-wind measurements in Part I, Chapter 12, Annex 12.B, Table 12.B.1 is 200 to 500 m in the troposphere and 1 km in the stratosphere, in practice there is information in the rawinsonde measurement which should be archived and reported for reasons other than numerical weather prediction analyses. So, it is recommended that, where possible, systems should use the higher resolution now available, with vertical resolution better than or equal to 200 m in the lower troposphere, and better than 300 m in the upper troposphere and lower stratosphere. As can be seen, there are strong shears near the jet maximum, and to resolve these reliably requires a vertical resolution better than the 500 m quoted in Table 12.B.1.

A vertical resolution of 50 to 150 m can prove beneficial for general meteorological operations in the atmospheric boundary layer (up to 2 km above the surface). However, the tracking system used must be able to sustain acceptable wind measurement accuracy at the higher vertical resolution if the increased resolution is to be useful.

Very high-accuracy upper-wind measurements are often specified for range operations such as rocket launches. In this case, special balloons with sculptured surfaces which follow the winds more closely than standard meteorological balloons must be used. The observing schedules required to meet a very high-accuracy specification need careful planning since the observations must be located close to the required site and within a given time frame. The following characteristic of atmospheric variability should be noted. The root-mean-square vector differences between two error-free upper-wind observations at the same height (sampled at the 300 m vertical resolution) will usually be less than 1.5 m s^{-1} if the measurements are simultaneous and separated by less than about 5 km in the horizontal. This will also be the case if the measurements are at the same location, but separated by an interval of less than about 10 min (derived from similar, smaller-scale studies to the representativeness studies of Kitchen (1989)).

13.1.3.4 ***Maximum height requirements***

Upper winds measured from balloon-borne equipment, as considered in this chapter, can be required at heights up to and above 35 km at some sites, especially those designated as part of the Global Climate Observing System. The balloons necessary to reach these heights may be more expensive than the cheap, small balloons that will lift the rawinsonde systems to heights between 20 and 25 km.

An ideal upper-wind observing network must adequately sample all scales of motion, from planetary scale to mesoscale, in the troposphere and lower stratosphere. The observing network will also identify significant small-scale wind structures using high temporal resolution remote-sensing systems. However, in the middle and upper stratosphere, the predominant scales of motion observed for meteorological operations are larger, primarily the planetary scale and larger synoptic scales. Thus, all the upper-air observing sites in a national network with network spacing being optimized for tropospheric observations may not need to measure to heights above 25 km. Overall operating costs may be less if a mix of the observing systems described in this chapter with the sensing systems described in Part II is used. If this is the case, national technical infrastructure must be able to provide adequate maintenance for the variety of systems deployed.

13.1.4 **Methods of measurement**

Data on upper winds from balloon-borne systems are mainly acquired by using rawinsonde techniques, although pilot-balloon and radiowind observations may be used when additional upper wind data are required without the expense of launching a radiosonde. Observations from the upper-air stations in the Global Observing System are supplemented over land by measurements from aircraft, wind profilers and Doppler weather radars. In areas with high levels of aircraft operations, the information available from aircraft and radars dominates that available from radiosondes up to heights of about 12 km. Over the sea, upper winds are mainly produced by civilian aircraft at aircraft cruise levels. These are supplemented with vertical profiles from rawinsondes launched from ships or remote islands, and also by tracking clouds or water vapour structures observed from geostationary meteorological satellites. In the future, wind measurements from satellite-borne lidars (light detection and ranging) and radars are expected to improve the global coverage of the current observing systems. Sodars (sound detection and ranging), lidars and kite anemometers are also used to provide high temporal resolution winds for specific applications. Low-cost pilotless aircraft technology is being developed for meteorological applications.

Rawinsonde methods for measuring the speed and direction of the wind in the upper air generally depend upon the observation of either the movement of a free balloon ascending at a more or less uniform rate or an object falling under gravity, such as a dropsonde on a parachute. Given that the horizontal motion of the air is to be measured, the target being tracked should not have any significant horizontal motion relative to the air under observation. The essential information required from direct tracking systems includes the height of the target and the measurements of its plan position or, alternatively, its horizontal velocity at known time intervals. The accuracy requirements in Part I, Chapter 12, Annex 12.A, include the effect of errors in the height or pressure assigned to the wind measurement. It is unlikely that the usual operational accuracy requirements can be met for levels above the atmospheric boundary layer with any tracking method that needs to assume a rate of ascent for the balloon, rather than using a measurement of height from the tracking system or from the radiosonde attached to the target.

Remote-sensing systems measure the motion of the atmosphere by scattering electromagnetic radiation or sound from one or more of the following targets: hydrometeors, dust, aerosol, or inhomogeneities in the refractive index caused by small-scale atmospheric turbulence or the air molecules themselves.

The direct windfinding methods considered in this chapter use targets whose position can be tracked continuously. While the targets can be tracked by a large number of methods, only two widely used types of methods will be considered here.

13.1.4.1 ***Tracking using radionavigation signals***

A radiosonde with the capability of receiving signals from a system of navigational radio transmitters is attached to a target (either an ascending balloon or dropsonde parachute). The most widely used system is to use signals from navigation satellites. In practice, for the moment, this means using the NAVSTAR GPS signals, although other, more recently introduced satellite radionavigation services may be used in the future. The signals from the satellites are received by a dedicated antenna on the radiosonde. The system will also have a GPS antenna on the ground to receive signals for reference. A GPS engine, either on the ground or in the radiosonde, will decode the signals or allow computation of the radiosonde position in three dimensions as a function of time.

Tracking using radionavigation signals was first achieved on a large scale with the surface-based Omega navigation chain, but once this service was closed most of these radiosonde operators changed to GPS windfinding. Surface-based long-range navigation signals were also used from the LORAN system, described in WMO (1985). The coverage offered by LORAN-C coupled with the Russian Chayka system has decreased in recent years, and now operational use is mainly limited to eastern Europe at the times that Chayka is operational.

The use of GPS navaid tracking has increased in routine meteorological operations because of the high degree of automation that can be achieved with this type of windfinding system. The level of maintenance required by navaid ground equipment is also very low. Height measurements from the GPS radiosonde provide the best method for assigning heights for accurate stratospheric temperatures in climate studies.

Early GPS radiosondes all used the meteorological aids (MetAids) frequency band centred at 403 MHz for transmitting data to the ground, but there are a few countries where large-scale civilian radiosonde operation in this band is not feasible, and GPS radiosondes using the higher frequency MetAids band centred at 1 680 MHz have also been developed.

13.1.4.2 *Tracking using a directional aerial*

In many large national networks the higher cost of GPS radiosonde consumables has meant that non-GPS radiosondes continue to be used with a ground system that tracks the target with a directional aerial measuring azimuth, plus any two of the following parameters: elevation angle, slant range, and height. Measurements are mostly achieved using a radiotheodolite or secondary radar (see section 13.2.3.2) to track a radiosonde carried by a balloon. In some cases, an optical theodolite is used to track the balloon. A primary radar (see section 13.2.3.1) can also track a reflecting target carried by the balloon, but although this system was quite widely used in the past, it is not in common use now. The difference between primary and secondary radars is that the primary radar detects pulses reflected from its target, while the secondary radar only transmits pulses and does not look for reflections. With a secondary radar, the radiosonde/transponder attached to the balloon receives the radar pulses and then transmits information on the time of receipt back to the radar ground station. Radar and radiotheodolite systems usually have a tracking accuracy for elevation and azimuth of about 0.1°, while for radar systems, the range error should normally be less than 30 m.

Modern radiotheodolite systems with antenna dimensions of less than 2 m are best suited for upper-wind measurements when balloon elevations stay above 10° to 15°. Secondary radar systems continue to be used in national networks where sufficient radio-frequency spectrum in the meteorological aids bands is available. Successful directional antennas are operated mostly in the 1 680 MHz band, as the antenna size required for directional tracking at 403 MHz is too large for most modern operational practice.

The choice between using a radiotheodolite or GPS radiosonde for upper-wind measurements will be partly influenced by the maximum slant range expected at the observation site. The GPS windfinding system will provide good measurement accuracy at very long ranges. The maximum range varies considerably with latitude, with 70 km being adequate in equatorial and polar regions, but with ranges of up to at least 200 km being possible in some mid-latitude temperate zones. Table 13.1 shows the proportion of occasions when certain slant ranges were exceeded for a balloon at 30 km. The data are for stations located in Europe between 50°N and 60°N. The proportions are given for a whole year, but it should be noted that the soundings which exceeded the limits were centred in the winter season.

13.2 UPPER-WIND SENSORS AND INSTRUMENTS

Radiowind systems were originally introduced to allow measurements of upper wind in the presence of clouds. The systems were also capable of high measurement accuracy at long ranges when balloons were tracked up to heights of 30 km. The use of these systems is now essential to satisfy the majority of modern upper-wind accuracy requirements. The high degree of automation possible with most modern rawinsonde systems has eliminated the need for operator intervention in most of the measurement cycle. This has major advantages in reducing costs for meteorological operations.

13.2.1 Optical theodolite

Optical theodolites may be used for tracking balloons when the expense of radiowind measurements cannot be met, for example at intermediate times between main ascents or at other locations in a country to fill gaps in the network at lower levels (see WMO, 2008).

Table 13.1. Proportion of occasions when certain slant ranges were exceeded (balloon at 30 km altitude)

Slant range exceeded (km)	140	160	175	190
Proportion of occasions (%)	5	2	1	0.5

Operators need significant training and skill if upper-wind measurement errors are not to increase rapidly as the balloon ascends above the boundary layer, but useful periods of observation have been achieved in parts of South America and Africa.

The optical system of the pilot balloon theodolite should be such that the axis of the eyepiece remains horizontal irrespective of the direction in which the telescope is pointed. A pentagonal prism is preferable to a right-angled prism since a slight displacement of the former does not affect the perpendicularity of the two parts of the optical axis.

The focusing eyepiece of the telescope should be fitted with cross-wires or a graticule and should have a magnification of between 20 and 25 times and a field of view of no less than 2°. The mounting of the theodolite should be of robust construction. It should be possible to turn the theodolite rapidly by hand or slowly by friction or worm gearing on the azimuth and elevation circles. These circles should be subdivided into sections no larger than 1° and should be provided with verniers or micrometer hand wheels allowing the angles to be read to 0.05°, with estimation possible to 0.01°. The scales should be arranged and illuminated so that readings can be taken by day and night. Backlash in the gearing of the circles should not exceed 0.025°. Errors in horizontal and vertical collimation should not exceed 0.1°.

The theodolite should be fitted with open sights to facilitate the tracking of a rapidly moving balloon. A secondary telescope with a wide field of view of no less than 8° is also useful for this purpose.

The base of the theodolite should be designed to fit into a standard tripod or other support and should incorporate some means of adjustment to allow accurate levelling. It should be possible to adjust the supports to suit the height of the observer. The theodolite should be of robust construction and should be protected against corrosion.

The system should be used with a suitable computer programme for inputting and checking the observational data for errors.

13.2.2 **Radiotheodolite**

Radiotheodolite windfinding is best suited to situations where the balloon elevations from the ground station remain high throughout the flight. If the balloon elevations remain above about 16°, most of the upper-wind accuracy requirements in Part I, Chapter 12, can be met with relatively small tracking aerials. At low balloon elevations, the measurement errors with radiotheodolites increase rapidly with decreasing elevation, even with larger tracking aerials (see section 13.5.3). It is extremely difficult to satisfy the accuracy requirements of Part I, Chapter 12, with a radiotheodolite if upper winds are consistently very strong, unless a transponder is used to provide a measurement of the slant range (see section 13.2.3.2).

A radiotheodolite is usually used to track the emissions from a radiosonde suspended beneath a weather balloon. A directional aerial coupled to a radio receiver is rotated around the vertical and horizontal axes to determine maximum signal strength using suitable servo-mechanisms. The radio frequency employed is usually 1 680 MHz. A good aerial design with a diameter of about 2 m should have low sensitivity in its side lobes relative to the main beam; with this size, angular tracking of 0.1° accuracy can be achieved. If this is the case, the radiotheodolite should be able to track at elevations as low as 6° to 10° without interference between signals received directly from the radiosondes and those received by reflection from adjacent surfaces. Interference between direct and reflected signals is termed multipath interference and is usually the limiting factor in radiotheodolite tracking capability at low elevations. The amount of multipath interference depends very critically on the positioning of the antenna relative to adjacent reflecting surfaces, whether the radiotheodolite is positioned on a roof or on the ground.

Detailed descriptions of the radiotheodolite aerial performance, detection system, servo-controls, and data-processing algorithms should be obtained from the manufacturer prior to purchase. Modern portable radiotheodolites with aerial dimensions of less than 2 m can encounter multipath interference problems at elevations as high as 16°. When multipath interference occurs, the maximum signal will not usually be found in the direction of the balloon. The elevation error varies with time as the multi-path interference conditions change as the radiosonde moves; this can lead to large systematic errors in wind data (greater than 10 m s^{-1}).

While the radiotheodolite is tracking the radiosonde, the observed azimuth and elevation angles are transmitted from the radiotheodolite to the ground system computer. The incoming radiosonde measurements give, with time, the variation of geopotential height corresponding to the observed directions. The rates for the change in the position of the balloon can then be derived. The computer should display the upper-wind measurements in tabular or graphical form. The continuity of winds in the vertical will allow the operator to check for faulty tracking. Once the operator is satisfied that tracking is adequate, a suitable upper-wind report can be issued to users.

Balloons will sometimes reverse direction shortly after launch because of marked wind shear just above the surface. The balloon will fly back over the radiotheodolite even though it is launched so that it should move away from the radiotheodolite. If the radiotheodolite is to sustain accurate automated tracking when this happens, it must be capable of very high scan rates in azimuth and elevation. This leads to a more demanding mechanical specification than is necessary for the majority of the flights when the balloon is at longer ranges. In order to reduce the mechanical specification needed for accurate tracking, several modern radiotheodolite designs incorporate interferometric tracking. In these systems, the interferometer compares the phase of the signals arriving at different sections of its tracking aerial in order to determine the position of the transmitting source relative to the aerial orientation. In practice, the phase data are sampled at a high rate using microprocessors, while a simple servo-mechanism orientates the aerial approximately in the direction of the radiosonde. The approximate orientation of the aerial is necessary to provide a good signal-to-noise ratio for the interferometer and to minimize the reflections received from the ground. The elevation and azimuth are then derived from a combination of aerial positions, while the direction to the source is deduced by the interferometer from the phase measurements. The measurement accuracy achieved is similar to that of the better standard radiotheodolites. The interferometric radiotheodolite systems are often more reliable and cheaper to maintain.

13.2.3 Radar

13.2.3.1 *Primary radars*

The essential feature of the radar-tracking technique compared to the radiotheodolite method is that slant range is measured directly together with azimuth and elevation. A primary radar relies on the detection of pulses of ultra-short radio waves reflected from a suitable target carried by the balloon. With a reliable primary radar, the accuracy requirements for upper winds outlined in Part I, Chapter 12, can be met in almost all circumstances. Very high-accuracy specifications for upper winds can be met with high-precision tracking radars, but in practice these are very expensive to use. For measurement accuracy better than about 1 m s^{-1} it is essential to use balloons with sculptured surfaces (which are also very expensive) rather than standard meteorological balloons.

A radiosonde does not have to be used in order to determine winds with a primary radar, a suitable reflector is enough. Substantial savings from minimizing expenditure on radiosondes might be possible as long as there is a technical support structure to maintain the radar and staff costs are very low. However, the use of primary radar as a windfinding tool to provide cheap operational measurements has not been successful in developing countries, with equipment rarely being maintained; in most countries, GPS radiosondes or radiotheodolites are now used.

13.2.3.2 *Secondary radars*

In secondary radar systems, pulses of energy transmitted from the ground station are received by a responder system carried by the balloon. This can either be a separate transponder package or a feature that is incorporated in the basic radiosonde design. The frequency of the return signal does not necessarily have to be the same as that of the outgoing signal. The time taken between the transmission of the pulse and the response from the responder allows the slant range to be measured directly. This type of system is still in widespread use in large national networks.

The advantage of this technique over a primary radar is that tracking can be sustained to longer ranges for a given power output from the ground transmitter. This is because the energy transmitted by the responder is independent and usually larger than the energy received from the ground transmitter. Thus, the energy received at the ground receiver is inversely proportional to the square of the slant range of the target. The energy received is inversely proportional to the fourth power of the slant range in the case of a primary radar.

The complexity of the system and the maintenance requirements of a secondary radar system usually fall between that of radiotheodolites and primary radars. The network managers must be able to ensure that the systems are well maintained. For instance, in the Russian Federation some older systems (see Table 13.4) of good tracking performance and which are in widespread use but difficult to maintain are now being replaced by improved ground tracking systems, which are relatively easy to maintain (see WMO, 2005).

13.2.4 **Navaid tracking systems**

In navaid tracking systems, the radiosonde incorporates an aerial system which receives the signals from a radionavigation system. This radionavigation system will be operated by agencies independent of the national weather Services. The navaid systems currently used operationally for windfinding are the satellite-based GPS giving global coverage, and LORAN systems using ground-based transmitters with very limited area of coverage.

One of the main advantages of navaid systems is the simplicity of the ground system, which does not consist of moving parts and does not need very accurate alignment of tracking aerials. This makes the systems suitable for deployment from aircraft and ships, as well as from land-based sites.

In order to keep the costs of signal processing in the radiosonde to a minimum, the majority of the processing to produce wind measurements from LORAN signals is performed after the radiosonde has relayed the navaid signals back to the ground system. Thus, good reception from the radiosonde is essential for this windfinding system; the siting of the ground system aerials must provide a good line of sight to the radiosondes in all directions. As the cost of GPS engines which process the GPS signals reduces, it is possible to perform much of the processing of the GPS signals on the radiosonde, although some processing on the ground is required to incorporate the information from the GPS reference signals received by a local ground-based antenna. In normal operation, the accuracy of GPS radiosonde position measurements does not reduce significantly with range from the ground stations (see WMO, 2011*b*).

The main operational problems with modern operational GPS radiosondes have been when there are radio transmitters in the vicinity at frequencies which cause interference to the reception of GPS signals by the radiosonde.

Height is assigned to upper-wind measurements using the radiosonde geopotential height measurements. It is vital that time stamping of the processed navaid wind data by the ground system is accurately aligned with the time stamping of the radiosonde height measurements.

13.2.4.1 ***Availability of navaid signals in the future***

International navigational operations have mainly moved to navigation using signals from the array of GPS navigational satellites orbiting the Earth. These satellite signals have largely replaced reliance on signals from fixed terrestrial transmitters. The other global satellite navigation service in operation is GLONASS, in the Russian Federation. BeiDou (COMPASS), in China, and Galileo, in Europe, are also in early stages of operation, in preparation for use as global services before 2020. A limited number of countries have chosen to persist with LORAN terrestrial navigational systems for regional or national navigational networks. Navigation authorities must be consulted as to the future availability of signals before any long-term investment in a given system is considered.

Although the computation of winds using GPS navigation is more complex than with navaid signals from terrestrial transmitters because the satellites move continuously relative to the radiosondes, the development of the GPS radiosonde systems is now mature, and 11 commercial systems were thus able to be tested in Yangjiang, China (see WMO, 2011*b*). Very few designs had any significant problems, with most having adequate signal reception (signals from between five and eight satellites received at a given time) and suitable processing algorithms relating the GPS signals received by the radiosonde to the signals received by a reference antenna at the ground station.

13.2.4.2 ***Global positioning system***

GPS radiosondes are now used at about half of the active global radiosonde network stations.

NAVSTAR GPS is a very high-accuracy radionavigation system based on radio signals transmitted from a constellation of 25 satellites orbiting the Earth in six planes. Each of the orbital planes intersects the Equator at a spacing of 60°, with the orbit planes inclined at 55° to the polar axis. An individual satellite orbits during a period of about 11 h and 58 min. The constellation of satellites is configured so that in any location worldwide a minimum of four satellites appear above the horizon at all times, but, in some situations, up to eight satellites may be visible from the ground.

The signals transmitted from the satellites are controlled by atomic frequency standards intended to provide a frequency stability of better than $1 \cdot 10^{-13}$. Each satellite transmits two unique pseudo-random digital ranging codes, along with other information including constellation almanac, ephemeris, UTC time and satellite performance. The ranging codes and system data are transmitted using biphase digital spread spectrum technology. The power level of the ranging code signals is –130 dBm, well below thermal background noise.

The following codes are taken into consideration:

(a) The coarse acquisition code is transmitted on a carrier at 1 575.42 MHz. This is modulated by a satellite-specific pseudo-random noise code with a chipping rate of 1.023 MHz. This modulation effectively spreads the coarse acquisition spectrum width to 2 MHz;

(b) The precision code may be replaced by a military controlled Y-code during periods when anti-spoofing is active. The precision code and system data are transmitted coherently on carriers L1 (1 575 MHz) and L2 (1 228 MHz).

The wavelengths of the GPS signals are very much shorter than for LORAN. The much smaller aerial used for receiving the GPS signals is positioned at the top of the radiosonde body and should be free of obstructions in all directions towards the horizon. The small aerial is better protected from the damaging effects of atmospheric electricity than LORAN aerials. Although the siting of the GPS aerial could cause a conflict with siting of the temperature sensor on the radiosonde, this has now been overcome in the designs available.

The GPS signals need to be pre-processed on the radiosonde to reduce the GPS information to signals that can be transmitted to the ground station on the radiosonde carrier frequency (either as analogue information, as used for LORAN, or as a digital data stream). The pre-processing can be carried out by a variety of techniques. Modern GPS radiosondes use the precision code in a differential mode. This requires simultaneous reception of the GPS signals by a receiver at the ground station as well as the receiver on the radiosonde. Accurate wind computations require signals from a minimum of four satellites. In a differential mode, the phase of the signals received at the radiosonde is referenced to those received at the ground station. This is especially beneficial when the radiosonde is near the ground station, since location errors introduced by propagation delays from the spacecraft to the receivers or by anti-spoofing are similar in both receivers and can be eliminated to a large extent.

GPS tracking systems are able to track accurately at a very high sample rate (rates of a few seconds). Thus, it is possible to measure the modulation of apparent horizontal velocity when the radiosonde swings as a pendulum under the balloon during a period of about 10 to 15 s. Most of the small differences found between GPS radiosonde wind measurements in Yangjiang, China, resulted from the use of different algorithms to filter out the balloon motion, with the algorithm often tuned to suit a particular configuration of radiosonde suspension and not that used in the radiosonde comparison test (WMO, 2011*b*).

One of the practical considerations with GPS radiosondes is the time taken for the GPS tracker on the radiosonde to synchronize with the signals being received from the satellite. It is unwise to launch the radiosonde before this synchronization has been achieved. This may require placing the radiosonde outside for several minutes before launch or, alternatively, a method for transmitting GPS signals to the radiosonde at the location where it is being prepared.

13.2.4.3 ***LORAN-C chains***

The LORAN-C system is a relatively long-range navaid operating in the low frequency band centred on 100 kHz (wavelength 3 km). Because its primary purpose was for marine navigation, particularly in coastal and continental shelf areas, LORAN-C coverage was provided only in certain parts of the world. These were mostly in maritime areas of the northern hemisphere. Some of the chains have been refurbished under new ownership to provide regional or national marine navigational networks.

A LORAN-C transmission consists of groups of eight or nine pulses of the 100 kHz carrier, each being some 150 μs in duration. Each chain of transmitters consists of one master station and two or more slaves. In principle, chain coherence is established by reference to the master transmission. Each slave transmits its groups of pulses at fixed intervals after the master, at a rate that is specific to a given chain. Typically this rate is once every 100 μs.

The LORAN-C signals propagate both as ground and sky waves reflected from the ionosphere. The ground waves are relatively stable in propagation. There are only very small phase corrections which are dependent on whether the signals are propagating across land or sea. The rate of change of the phase corrections as the radiosonde position changes is not usually large enough to affect wind measurement accuracy. Sky wave propagation is more variable since it depends on the position of the ionosphere and will change with time of day. Ground wave signals from the transmitter are much stronger than sky waves, but sky waves attenuate much less rapidly than ground waves. Thus, the best situation for LORAN-C windfinding is obtained when the signals received at the radiosonde from all the transmitters are dominated by ground waves. This can be achieved in parts of the LORAN-C service areas, but not at all locations within the theoretical coverage.

The LORAN-C radiosonde receives the signals through its own aerial and then modulates the radiosonde carrier frequency in order to transmit the signals to the radiosonde receiver. The LORAN tracker used to detect the times of arrival of the LORAN pulses should be able to differentiate between ground and sky wave signals to some extent. This is achieved by detecting the time of arrival from the leading sections of the pulses. Modern LORAN trackers are able to operate in cross-chain mode, so that signals from more than one LORAN chain can be used together. This facility is essential for good-quality wind measurements in many parts of the LORAN-C service areas. Winds are computed from the rates of change in the time of arrival differences between pairs of LORAN-C transmitters. The computations use all the reliable LORAN-C signals available, rather than a bare minimum of three.

The use of LORAN navigation for operational radiosondes is now very limited.

13.3 MEASUREMENT METHODS

13.3.1 General considerations concerning data processing

Modern tracking sensors can take readings much more frequently than at the 1 min intervals commonly used with earlier manual systems. The processing of the winds will normally be fully automated using an associated ground system computer. The upper winds will be archived and displayed by the operator for checking before the information is issued to users.

Thus, the sampling of tracking data is optimal at intervals of 10 s or less. Sampling should be at the highest rate considered useful from the tracking system. High sampling rates make it easier to control the quality of the data with automated algorithms. After editing, the tracking data can then be smoothed by statistical means and used to determine the variation in position with time, if required. The smoothing applied will determine the thickness of the atmospheric layer to which the upper-wind measurement applies. The smoothing will often be changed for different parts of the flight to account for the differing user requirements at different heights and the tracking limitations of the upper-wind system used. If measurement accuracy drops too low at higher levels, the vertical resolution of the measurement may have to be reduced below the optimum requirement to keep the wind measurement errors within acceptable limits.

Effective algorithms for editing and smoothing may use low-order polynomials (Acheson, 1970), or cubic splines (de Boor, 1978). Algorithms for computing winds from radar and radiotheodolite observations can be found in WMO (1986). In general, winds may either be derived from differentiating positions derived from the tracking data, or from the rates of change of the smoothed engineering variables from the tracking system (see Passi, 1978). Many modern systems use this latter technique, but the algorithms must then be able to cope with some singularities in the engineering variables, for instance when a balloon transits back over the tracking site at high elevation.

When the winds computed from the tracking data are displayed for checking, it is important to indicate those regions of the flight where tracking data were missing or judged too noisy for use. Some of the algorithms used for interpolation may not be very stable when there are gaps in the tracking data. It is important to differentiate between reliable measurements of vertical wind shear and shears that are artefacts of the automated data processing when tracking data are absent. Tracking data are often of poor quality early in a balloon ascent. If the upper-wind system is unable to produce a valid wind measurement shortly after launch, it is preferable to leave a gap in the reported winds until valid tracking data are obtained. This is because interpolation between the surface and the first levels of valid data often requires interpolation across layers of marked wind shear in the vertical. The automated algorithms rarely function adequately in these circumstances.

13.3.2 Pilot-balloon observations

The accurate levelling and orientation of the optical theodolite with respect to the true north are an essential preliminary to observing the azimuth and elevation of the moving balloon. Readings of azimuth and elevation should be taken at intervals of no less than 1 min. Azimuth angles should be read to the nearest tenth of a degree. In a pilot-balloon ascent, the elevation angles should be read to the nearest tenth of a degree whenever the angles are 15° or greater. It is necessary to measure elevation to the nearest 0.05° whenever the angles are less than 15°.

If a radiosonde ascent is being followed by optical theodolite, a higher upper-wind measurement accuracy can be achieved at lower elevations. Thus, the elevation angles should be read to the nearest tenth of a degree whenever the angles are greater than 20°, to the nearest 0.05° whenever the angles are 20° or less, but greater than 15°, and to the nearest 0.01° whenever the angles are 15° or less. Timing may be accomplished by either using a stop-watch or a single alarm clock which rings at the desired intervals.

In single-theodolite ascents, the evaluation of wind speed and direction involves the trigonometric computation of the minute-to-minute changes in the plane position of the balloon. This is best achieved by using suitable computer software.

If higher accuracy is required, the double-theodolite technique should be used. The baseline between the instruments should be at least 2 km long, preferably in a direction nearly at right angles to that of the wind prevailing at the time. Computations are simplified if the two tracking sites are at the same level. Communication between the two sites by radio or land-line should help to synchronize the observations from the two sites. Synchronization is essential if good measurement accuracy is to be achieved. Recording theodolites, with the readings logged electronically, will be helpful in improving the measurement accuracy achieved.

For multiple-theodolite tracking, alternative evaluation procedures can be used. The redundancy provided by all the tracking data allows improved measurement accuracy, but with the added complication that the calculations must be performed on a personal computer (see Lange, 1988; Passi, 1978).

13.3.3 **Observations using a directional aerial**

Windfinding systems that track using directional aerials require very careful installation and maintenance procedures. Every effort must be made to ensure the accuracy of elevation and azimuth measurements. This requires accurate levelling of the installation and careful maintenance to ensure that the orientation of the electrical axis of the aerial remains close to the mechanical axis. This may be checked by various methods, including tracking the position of local transmitters or targets of known position. Poor alignment of the azimuth has caused additional errors in wind measurement at many upper-air stations in recent years.

The calibration of the slant range of a primary radar may be checked against known stationary targets, if suitable targets exist. The tracking of the radar in general may be checked by comparing radar geopotential heights with simultaneous radiosonde measurements. The corrections to the radar height measurements for tracking errors introduced by atmospheric refraction are discussed in section 13.7.

The comparison of radar height measurements with GPS radiosonde geopotential heights may be used to identify radar tracking which fails to meet the standards. Furthermore, if the radar slant range measurements are known to be reliable, it is possible to identify small systematic biases in elevation by comparing radar heights with radiosonde heights as a function of the cotangent of elevation. The typical errors in GPS radiosonde geopotential heights were established for the most widely used radiosondes by WMO (2011*b*).

Both radar and radiotheodolite systems can encounter difficulties when attempting to follow a target at close ranges. This is because the signal strength received by a side lobe of the aerial may be strong enough to sustain automated tracking at short ranges; however, when tracking on a side lobe, the signal strength received will then drop rapidly after a few minutes and the target will apparently be lost. Following target loss, it may be difficult to recover tracking with some systems when low cloud, rain or fog is present at the launch site. Thus, it is necessary to have a method to check that the target is centred in the main beam early in flight. This check could be performed by the operator using a bore-sight, telescope or video camera aligned with the axis of the aerial. The tracking alignment is more difficult to check with an interferometric radiotheodolite, where the mechanical tracking of the radiotheodolite will not necessarily coincide exactly with the observed direction of travel of the balloon.

13.3.4 **Observations using radionavigation systems**

The development of observations using GPS winds was first reported by Call (WMO, 1994) and Kaisti (1995). These systems did not decode the GPS signals received, but they have now been superseded by GPS radiosondes that do decode the signals.

The geometry for using satellite navigation signals is such that GPS windfinding algorithms seem to work most reliably when signals are received from at least five satellites during the ascent. The GPS almanac can be used to identify times when satellite geometry is weak for windfinding. In practice, this rarely occurs with the current satellite configuration and the good satellite reception antenna used with modern radiosondes.

When making upper-wind measurements with navaid tracking systems, the ground system navaid tracker should be accurately synchronized to the navaid transmissions prior to launch. Synchronization is usually achieved by using signals received by a local aerial connected to the ground system receiver. This aerial should be capable of receiving adequate signals for synchronization in all the weather conditions experienced at the site. The ground system should provide clear indications to the operator of the navaid signals available for windfinding prior to launch and also during the radiosonde flight. Where the GPS radiosonde is being used to make height measurements for the operational ascent, it is essential that the height of the local GPS antenna relative to the surface is accurately determined and entered into the ground station processing software.

Once launched, the navaid windfinding systems are highly automated. However, estimates of the expected measurement errors based on the configuration and quality of the navaid signals received would be helpful to the operators. During flight, the operator must be able to identify faulty radiosondes with poor receiver or transmitter characteristics which are clearly providing below-standard observations. These observations need to be suppressed and a re-flight attempted, where necessary.

Satisfactory upper-wind measurements from LORAN radionavigation systems require the radiosonde to receive signals from at least three LORAN stations. The difference in the time of arrival of the navigation signals received by the radiosonde, after coherent transmission from two locations, defines a locus or line of position (see WMO, 1985). This will have the shape of a hyperbola on a plane (but becomes an ellipse on the surface of a sphere). Thus, navigational systems using this technique are termed hyperbolic systems. Two intersecting lines of position are sufficient to define plan positions. However, there may be a large error in position associated with a small error in time of arrival if the lines of position are close to parallel when they intersect. With LORAN navaid upper-wind systems, it has been clearly demonstrated that all available navaid signals of a given type (usually at least four or five) should be used to improve tracking reliability. One type of algorithm used to exploit all the navaid signals available was outlined in Karhunen (1983).

13.4 EXPOSURE OF GROUND EQUIPMENT

An appropriate site for a radiotheodolite or radar is on high ground, with the horizon being as free from obstructions as possible. There should be no extensive obstructions subtending an angle exceeding 6° at the observation point. An ideal site would be a symmetrical hill with a downward slope of about 6° for a distance of 400 m, in a hollow surrounded by hills rising to a 1° or 2° elevation.

The tracking system should be provided with a firm foundation on which the equipment can be mounted. Good reception of signals by a local navaid aerial and by the ground system aerial for the radiosonde is essential if the navaid measurements are to be successful. These aerials should be mounted in positions on the upper-air site where there is a good horizon for reception in all directions.

Upper-wind measurements are usually reported in association with surface-wind measurements. It is preferable that surface wind be obtained from a site close to the balloon launch site. The launch site should be chosen to provide winds that are appropriate to the purpose of the upper-wind measurement. For example, if the upper-wind measurement is required to detect a localized effect influencing an airfield, the optimum location might differ from a site needed to observe mesoscale and synoptic scale motions over a larger area.

13.5 SOURCES OF ERROR

13.5.1 General

Errors in upper-wind measurements are a combination of the errors resulting from imperfect tracking of the horizontal motion of the target, the errors in the height assigned to the target, and the differences between the movement of the target and the actual atmospheric motion.

13.5.1.1 *Target tracking errors*

The relationship between wind errors and tracking errors differs according to the method of observation. For some systems, such as radiotheodolites, the wind errors vary markedly with range, azimuth and elevation, even when the errors of these tracking parameters remain constant with time. On the other hand, wind errors from systems using navaid tracking do not usually vary too much with range or height.

The uncertainties caused by the manual computation of wind were evaluated in WMO (1975). It was concluded that the risks of introducing significant errors by using manual methods for wind computations (such as plotting tables, slide rules, etc.) were too great, and that upper-wind computations should be automated as far as possible.

The measurement accuracy of all upper-wind systems varies from time to time. This variation may occur for short periods during a given target flight, when tracking temporarily degrades, or during an entire flight, for instance if the transmitted signals from a navaid radiosonde are faulty. At some locations, the accuracy of upper-wind tracking may gradually degrade with time over several months because of either instability in the tracking capability or the set-up of the ground system. In all cases, it would be helpful if estimates of wind measurement accuracy were derived by the upper-wind systems in real time to supplement the reported upper-wind measurements. The reported errors would allow poorer quality measurements to be identified and less weight would be given in numerical analyses. The reporting of errors could be achieved in practice by using the appropriate TEMP or PILOT codes and BUFR tables (WMO, 2011*a*).

When errors in target tracking start to introduce unacceptable wind errors at a given vertical resolution, the situation is usually compensated by computing the winds at a lower vertical resolution.

The practice of reducing the vertical resolution of upper-wind measurements in steps through the upper troposphere and lower stratosphere was mainly adopted to overcome the tracking limitations of radiotheodolites. This practice is not justified by the actual vertical structure observed in the atmosphere. Many of the larger vertical wind shears are found in the upper levels of jet streams at heights between 10 and 18 km (see, for instance, the detailed vertical wind profiles presented in Nash, 1994).

13.5.1.2 *Height assignment errors*

Height assignment errors for rawinsonde winds in the troposphere and lower stratosphere will be the same as those discussed for height measurements in Part I, Chapter 12. These errors will be highest for radiosondes using pressure sensors in the upper stratosphere, and would be most significant for numerical weather prediction or climate studies if there were significant wind shear in the vertical, such as in the polar-night vortex (see Figure 13.1(b)).

For pilot balloons tracked with a single theodolite, height is derived from time into flight, and the rate of ascent for the balloon is assumed. In practice, it is difficult to launch balloons with a precisely determined rate of ascent. Thus, where there is significant vertical shear in the vertical at low levels, possibly associated with significant differences in vertical velocity from thermals, pilot-balloon measurements could be adversely affected by the height assignment errors.

Prototype testing of fully automated upper-wind systems often reveals discrepancies between the times assigned to wind observations and those assigned to the associated radiosonde measurements. In some cases, the wind timing is not initiated at the same time as that of the radiosonde, in others synchronization is lost during flight for a variety of reasons. Times assigned to the reported winds are not always those corresponding to the data sample used to compute the wind, but rather to the time at the beginning or end of the sample. All types of timing error could produce large errors in the heights assigned to wind measurements and need to be eliminated during prototype testing if reliable operations are to be achieved.

13.5.1.3 *Target motion relative to the atmosphere*

The motion of the target relative to the air matters most for systems with the highest tracking accuracy and highest vertical resolution. For instance, the swinging of the GPS radiosonde under a balloon is clearly visible in the GPS tracking measurements and must be filtered out as far as possible.

The balloon motion relative to the atmosphere, introduced by the shedding of vortices by the balloon wake, may result in errors as large as 1 to 2 m s^{-1} (2σ level) when tracking small pilot balloons (50 g weight) at vertical resolutions of 50 m. Balloon motion errors are less significant in routine operational measurements (vertical resolutions of about 300 m) where measurements are obtained by tracking larger balloons (weight exceeding 350 g).

The horizontal slip of the dropsonde parachutes relative to the atmosphere may also be the limiting factor in the accuracy of GPS dropsonde measurements. The descent rates used in dropsonde deployments are usually about twice the ascent rate of operational radiosonde balloons.

13.5.2 **Errors in pilot-balloon observations**

The instrumental errors of a good optical theodolite are not likely to exceed ±0.05°. The errors may vary slowly with azimuth or elevation but are small compared with the errors introduced by the observer. Errors of reading scales should not exceed 0.1°. These errors become increasingly important at long ranges and when working at low elevations.

In single-theodolite ascents, the largest source of error is the uncertainty in the balloon rate of ascent. This uncertainty arises from variations in filling the balloon with gas, in the shape of the balloon, and in the vertical velocity of the atmosphere through which the balloon ascends. A given proportional error in the rate of ascent results in a proportional error in the height of the balloon and, hence, as modified by elevation angle, a proportional error in wind speed.

In double-theodolite ascents, the effect of system errors depends upon the method of evaluation adopted. Error analyses have been provided by Schaefer and Doswell (1978).

13.5.3 **Errors of systems using a directional aerial**

The relationship between vector wind errors and the errors of the actual tracking measurements can be expressed as an approximate function of height and mean wind (or ratio of the latter to the mean rate of ascent of the balloon). The relationships for random errors in primary radar and radiotheodolite wind measurements are as follows:

(a) Primary or secondary radar measuring slant range, azimuth and elevation:

$$\varepsilon_v^2 = 2 \cdot \left[\varepsilon_r^2 \cdot Q^2 \Big/ \left(Q^2 + 1\right) + \varepsilon_\theta^2 \cdot h^2 + \varepsilon_\varphi^2 \cdot h^2 \cdot Q^2 \right] \Big/ \tau^2 \qquad (13.3)$$

(b) Optical theodolite or radiotheodolite and radiosonde measuring azimuth, elevation angle and height:

$$\varepsilon_{\mathrm{v}}{}^2 = 2 \cdot \left[\varepsilon_h{}^2 \cdot Q^2 + \varepsilon_\theta{}^2 \cdot h^2 \cdot \left(Q^2+1\right)^2 + \varepsilon_\varphi{}^2 \cdot h^2 \cdot Q^2 \right] \Big/ \tau^2 \qquad (13.4)$$

where ε_{v} is the vector error in computed wind; ε_{r} is the random error in the measurement of slant range; ε_θ is the random error in the measurement of elevation angle; ε_φ is the random error in the measurement of azimuth; ε_h is the random error in height (derived from pressure measurement); Q is the magnitude of mean vector wind up to height h divided by the mean rate of ascent of the balloon up to height h; and τ is the time interval between samples.

Table 13.2 illustrates the differences in vector wind accuracy obtained with these two methods of upper-wind measurement. The mean rate of ascent used in upper-wind measurements will usually be in the range of 5 to 8 m s^{-1}. The vector wind error values are derived from equations 13.3 and 13.4 for various heights and values of Q, for a system tracking with the following characteristics: ε_{r} 20 m; ε_θ 0.1°; ε_φ 0.1°; ε_h height error equivalent to a pressure error of 1 hPa; τ 1 min.

Table 13.2 demonstrates that measurements with a radio (or optical) theodolite clearly produce less accurate winds for a given tracking accuracy than primary or secondary radars.

In the expressions for vector error in the computed winds in equations 13.3 and 13.4, the first two terms within the square brackets represent the radial error and the error in the winds observed with the same azimuth as the tracking aerial. The third term in the square brackets represents the tangential error, the error in winds observed at right angles to the azimuth of the tracking aerial. With these types of upper-wind systems, the error distribution is not independent of the directions and cannot be adequately represented by a single parameter. Thus, the values in Table 13.2 indicate the size of the errors but not the direction in which they act.

When the tangential and radial errors are very different in size, the error distribution is highly elliptic and the combined errors tend to concentrate either parallel to the axis of the tracking antenna or perpendicular to the axis. Table 13.3 shows the ratio of some of the tangential and radial errors that are combined to give the vector errors in Table 13.2. Values above 3 in Table 13.3 indicate situations where the tangential error component dominates. Thus, in radar windfinding, the tangential errors dominate at longer ranges (high mean winds and hence high Q values, plus largest heights). With radiotheodolite windfinding, the radial errors dominate at longer ranges

Table 13.2. 90% vector error (m s^{-1}) as a function of height and ratio Q of mean wind to rate of ascent

	Radar						*Radiotheodolite*					
Q	ε_v *5 km*	ε_v *10 km*	ε_v *15 km*	ε_v *20 km*	ε_v *25 km*	ε_v *30 km*	ε_v *5 km*	ε_v *10 km*	ε_v *15 km*	ε_v *20 km*	ε_v *25 km*	ε_v *30 km*
1	1	1	1.5	1.5	2.5	2.5	1	1.5	3	5.5	9	25
2	1	1.5	2.5	3	4	4	5	4	6.5	11	19	49
3	1.5	2.5	3	4	5	6	4	7	11	19	30	76
5	1.5	3	5	6	8	10	9	18	27	42	59	131
7	2.5	5	7	9	11	13	18	34	51	72	100	194
10	3	6.5	10	13	16	19	34	67	100	139	182	310

Notes:

a This table does not include the additional errors introduced by multipath interference on radiotheodolite observations. Additional errors can be expected from these effects for values of Q between 7 and 10.

b In practice, radiotheodolite wind observations are smoothed over thicker layers than indicated in these calculations at all heights apart from 5 km. Thus, at heights of 15 km and above, the radiotheodolite errors should be divided by at least a factor of four to correspond to operational practice.

Table 13.3. Ratio of upper-wind error components (α_{av} = tangential error/radial error α)

	Radar						Radiotheodolite					
Q	α_{av} 5 km	α_{av} 10 km	α_{av} 15 km	α_{av} 20 km	α_{av} 25 km	α_{av} 30 km	α_{av} 5 km	α_{av} 10 km	α_{av} 15 km	α_{av} 20 km	α_{av} 25 km	α_{av} 30 km
1	1/2	1	1	1	1	1	1/3	1/2	1/3	1/4	1/5	1/13
2	1	1	2	2	2	2	1/3	1/3	1/3	1/4	1/6	1/13
3	1	2	2	3	3	3	1/4	1/4	1/4	1/5	1/6	1/13
5	1	3	4	4	5	5	1/5	1/5	1/6	1/6	1/7	1/14
7	3	5	5	6	6	7	1/7	1/7	1/7	1/7	1/9	1/14
10	4	7	8	9	9	9	1/10	1/10	1/10	1/11	1/11	1/16

and the ratios become very much smaller than 1. Errors in elevation angle produce the major contribution to the radiotheodolite radial errors. However, random errors in the radiosonde height make the most significant contribution at high altitudes when values of Q are low.

The results in Tables 13.2 and 13.3 are based on a theoretical evaluation of the errors from the different types of systems. However, it is assumed that winds are computed from a simple difference between two discrete samples of tracking data. The computations take no account of the probable improvements in accuracy from deriving rates of change of position from large samples of tracking information obtained at high temporal resolution. Table 13.4 contains estimates of the actual measurement accuracy achieved by a variety of radars and radiotheodolites in the four phases of the WMO International Radiosonde Comparison (see section 13.6.1.2 for references to the tests).

Table 13.4. Estimates of the typical random vector errors (2σ level, unit: m s^{-1}) in upper-wind measurements obtained during the WMO International Radiosonde Comparison (estimates of typical values of Q and α_{av} for each of the four phases are included)

System	ε_v 3 km	α_{av} 3 km	Q 3 km	ε_v 18 km	α_{av} 18 km	Q 18 km	ε_v 28 km	α_{av} 28 km	Q 28 km	Test site
Primary radar (United Kingdom)	1.1	1	3.5	2.1	1.3	5	2.7	1.6	5	United Kingdom[a]
Radiotheodolite (United States)	2.1	≈ 1	1.5	4.8	≈ 1	2.5	5.2	≈ 1	1	United Kingdom
Radiotheodolite (United States)	2.8	≈ 1	2.5	10.4	0.4	6	9	0.33	4	United States
Radiotheodolite, portable	1.5	≈ 1	< 1	4.8	≈ 1	3	5.8	≈ 1	1.5	Kazakhstan
Radiotheodolite, portable	2.2	≈ 1	1.5	12	0.31	5.5	9	0.23	4	Japan
Radiotheodolite (Japan)	1.7	≈ 1	1.5	6.4	0.48	5.5	4.7	0.48	4	Japan
Secondary radar (AVK, Russian Federation)	1.5	≈ 1	< 1	2.6	≈ 1	3	2.6	≈ 1	1.5	Kazakhstan
Secondary radar (China)	1.5	≈ 1	< 1	3.8	≈ 1	3	3.4	≈ 1	1.5	Kazakhstan

Note:
a Data obtained in the United Kingdom test following Phase I of the WMO International Radiosonde Comparison (See Edge et al., 1986)

Of the three radiotheodolites tested in the WMO International Radiosonde Comparison, the Japanese system coped best with high Q situations, but this system applied a large amount of smoothing to elevation measurements and did not measure vertical wind very accurately in the upper layers of the jet streams. The smaller portable radiotheodolite deployed by the United States in Japan had the largest wind errors at high Q because of problems with multipath interference.

The ellipticity of the error distributions for radar and radiotheodolite observations showed the tendencies predicted at high values of Q. However, the ellipticity in the errors was not as high as that shown in Table 13.3, probably because the random errors in the rates of change of the azimuth and elevation were, in practice, smaller than those taken for Table 13.3.

In the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*), China used a modern secondary radar operating at 1 680 MHz with the Daqiao radiosonde system. When winds were strong in the lower troposphere, values of Q at a height of about 4 km were between 2 and 3, range was about 15 km, and the root-mean-square (RMS) vector errors ($k = 2$) in the winds were about 1 to 1.2 m s^{-1} with an ellipticity between 1 and 1.3. Towards the ends of the flights in the stratosphere, Q was again about 2.5 on average, but at the longer ranges of 70 to 100 km, ε_v for $k = 2$ was about 2.7 m s^{-1} and the ellipticity was 2. The reference winds in Yangjiang were GPS winds at a high vertical resolution, better than 150 m, whereas the vertical resolution of the working reference in Kazakhstan was 300 m at the best. Thus, the modern Chinese secondary radar was working well and is an improvement on the previous 403 MHz system.

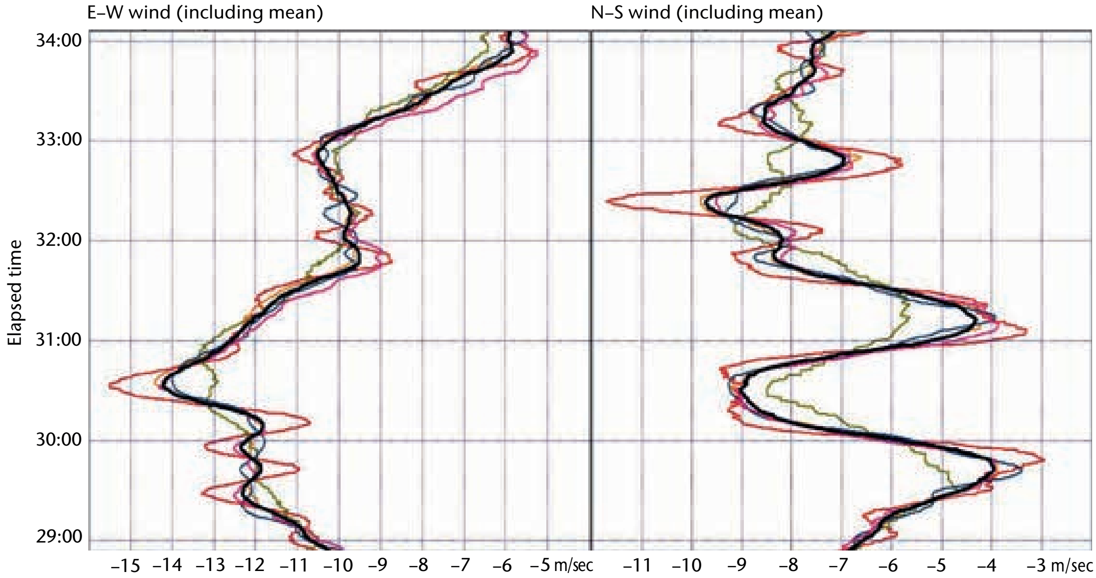
13.5.4 **Errors in the global positioning system windfinding systems**

In theory, GPS windfinding systems using coarse acquisition ranging codes in a differential mode should be capable of measuring winds to an uncertainty of 0.2 m s^{-1}. The estimates of accuracy in Table 13.5 were made on the basis of recent WMO tests of GPS radiosondes. The main difference between systems comes from the filtering applied to the winds to remove the motion of the radiosonde relative to the balloon. This motion is partly a regular pendulum of the radiosondes under the balloon, and partly some additional irregular rotation and displacement in reaction to differences between the winds experienced by the balloon and the radiosonde as the balloon ascent progresses.

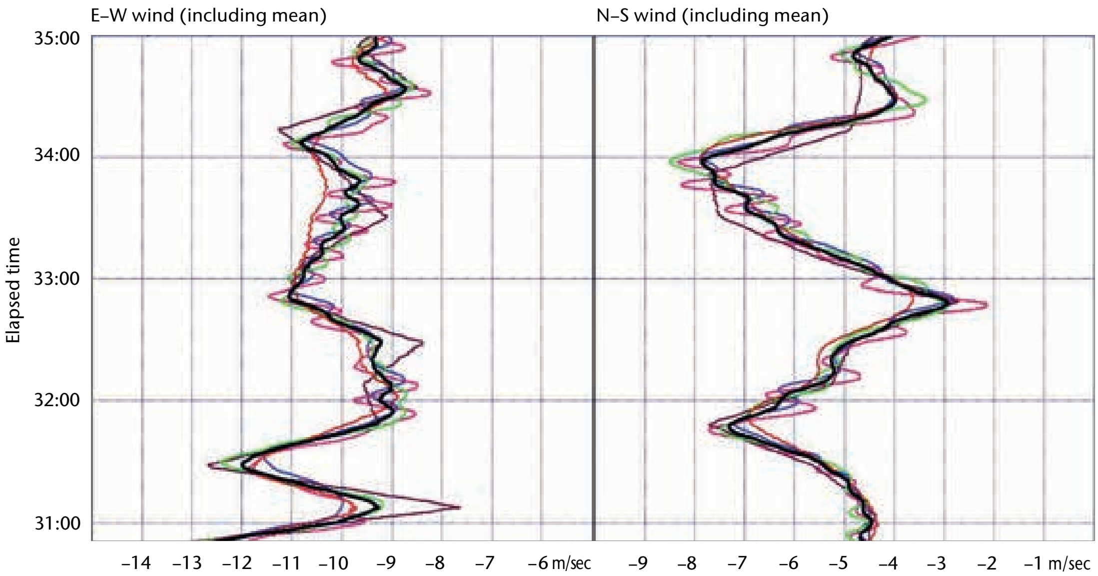
Examples of simultaneous observations of winds obtained in the upper troposphere from the GPS radiosondes in the WMO Intercomparison of High Quality Radiosonde Systems are shown in Figure 13.2. Only excerpts from the flights are shown because it is only when looking at a short sample of data from the flights that the differences can be seen, as the general agreement is much better than what the standard has been for earlier operational wind measurements.

The extracts in Figure 13.2 show that nearly all the systems agree well in resolving vertical structure with peaks in the wave structures separated by about 90 s, but not to the same extent for fluctuations where the peaks were separated by 40 s or less. Thus, the vertical wavelengths that generally resolved without any ambiguity were 600 m, but those where there was considerable ambiguity corresponded to 200 m or less. One system in Figure 13.2(a) was over-smoothed compared to the others, while one system in Figure 13.2(b) attempted to fit straight lines to the GPS measurements; both behaviours lead to outliers from the correct values on occasion.

These extracts, representing neither the best nor the worst, suggest that the processing of GPS wind measurements is relatively mature and that a large number of manufacturers have achieved satisfactory results. This was confirmed when the statistics from the 60 flights performed with operational GPS radiosondes in Yangjiang were generated (see Table 13.5). In this table, the wind differences (obtained from about 30 comparison flights) were averaged over either 2 min, 30 s or 10 s, and the best performance was attributed to the two systems with the lowest RMS vector differences. The errors found in Table 13.5 are good enough to meet the optimum user requirement for winds stated in Part I, Chapter 12, Annex 12.A.



(a) Flight 33: Jinyang, InterMet, Lockheed Martin Sippican, MODEM and Vaisala



(b) Flight 34: Changfeng, Graw, Huayun, Meisei and Meteolabor

Figure 13.2. Extracts from intercomparison flights of GPS winds made at Yangjiang, China, during the WMO Intercomparison of High Quality Radiosonde Systems (WMO, 2011*b*)

In time, the differences in the filtering of the GPS position measurements to minimize the effects of the radiosonde measurements relative to the balloon will probably reduce compared to the ranges indicated in Table 13.5. However, the irregular movements (as opposed to the relatively smooth pendulum motion) of the radiosonde relative to the balloon will limit the agreement that can be obtained between two radiosondes in a test flight. For the same reason, the error in an individual radiosonde measurement can be expected to be larger than might be computed given the expected accuracy of radiosonde position that can be obtained with the satellite radionavigation systems.

The external balloon of the double balloons used in China often burst near 16 km, and the resulting perturbations on the stability of the radiosonde motion may have led to the largest RMS vector errors near 16 km in Table 13.5. In UK tests (60 flights), conducted over several seasons in 2009/2010 on GPS radiosondes from two different manufacturers present in Yangjiang, results in the lower troposphere and the stratosphere were similar to those in Table 13.5. However, RMS

Table 13.5. Random vector error ($k = 2$) and systematic bias for good quality GPS navaid windfinding systems during the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China

Height range	*Systematic bias (m s⁻¹)*	*RMS vector error at 2 km vertical resolution (m s⁻¹)*	*RMS vector error at 300 m vertical resolution (m s⁻¹)*	*RMS vector error at 100 m vertical resolution (m s⁻¹)*
Lower troposphere 0–8 km	Up to ±0.05	0.06 – 0.15	0.12 – 0.50	0.3 – 0.7
Upper troposphere 8–17 km	Up to ±0.10	0.1 – 0.4[a]	0.3 – 0.9[a]	0.4 – 1.4[a]
Stratosphere 17–34 km	Up to ±0.15	0.15 – 0.40[b]	0.3 – 0.8[b]	0.4 – 1.1[b]

Notes:
a Poorest performance found at heights near 16 km
b Poorest performance found at heights greater than 28 km

vector wind errors in the upper troposphere were in the range 0.3 to 0.6 m s^{-1} at a vertical resolution of 100 m, and 0.2 to 0.5 m s^{-1} at a vertical resolution of 300 m. Thus, for these two systems the fine structure in the wind measurements in the United Kingdom in the upper troposphere agreed more closely than for the systems in Yangjiang.

On occasion, a GPS radiosonde malfunctions and does not report winds throughout a flight when reporting temperature and humidity until the balloon bursts. On some occasions, radio-frequency interference from an external source causes problems, and winds may have larger errors. The processing software needs to be able to inform the operator when problems like these are present, as it is difficult to distinguish between real atmospheric structure and measurements with large random errors (for example, see the wind profile in Figure 13.3).

Unlike the ground-based LORAN-C, the performance of the GPS winds will not vary significantly with conditions in the ionosphere.

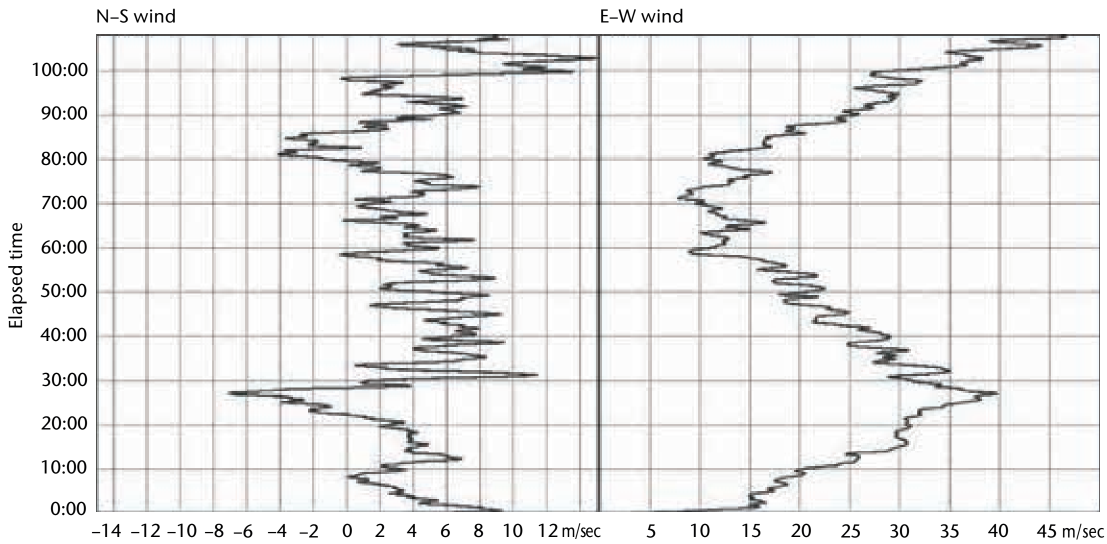


Figure 13.3. Example of a vertical wind profile measured independently by GPS radiosondes from two different manufacturers at Camborne, United Kingdom, and showing the small-scale structure which is present in many correct measurements. The radiosonde processing software needs to indicate which parts of a flight are less reliable when the reception of GPS signals is clearly not as reliable as usual.

13.5.5 Errors in ground-based LORAN-C radionavigation systems

Navaid system errors depend on the phase stability of navaid signals received at the radiosonde and upon the position of the radiosonde relative to the navaid network transmitters. However, the quality of the telemetry link between the radiosonde and the ground receiver cannot be ignored. In tests where radiosondes have moved out to longer ranges (at least 50 to 100 km), wind errors from the navaid windfinding systems are found to increase at the longer ranges, but usually at a rate similar to or less than the increase with the range for a primary radar. Signal reception from a radiosonde immediately after launch is not always reliable. LORAN-C wind measurements have larger errors immediately after launch than when the radiosonde has settled down to a stable motion several minutes into flight.

LORAN-C navaid wind measurement accuracy is mainly limited by the signal-to-noise ratios in the signals received at the radiosonde. Integration times used in practice to achieve reliable windfinding vary from 30 s to 2 min for LORAN-C signals. Signal strength received at a given location from some LORAN-C transmitters may fluctuate significantly during the day. This is usually because, under some circumstances, the diurnal variations in the height and orientation of the ionospheric layers have a major influence on signal strength. The fluctuations in signal strength and stability can be so large that successful wind measurement with LORAN-C may not be possible at all times of the day.

A second major influence on LORAN-C measurement accuracy is the geometric dilution of precision of the navigation system accuracy, which depends on the location of the radiosonde receiver relative to the navaid transmitters. When the radiosonde is near the centre of the baseline between the two transmitters, a given random error in the time of arrival difference from two transmitters will result in a small random positional error in a direction that is parallel to the baseline between the transmitters. However, the same random error in the time of arrival difference will produce a very large positional error in the same direction if the radiosonde is located on the extension of the baseline beyond either transmitter. The highest accuracy for horizontal wind measurements in two dimensions requires at least two pairs of navaid transmitters with their baselines being approximately at right angles, with the radiosonde located towards the centre of the triangle defined by the three transmitters. In practice, signals from more than two pairs of navaid transmitters are used to improve wind measurement accuracy whenever possible. Techniques using least squares solutions to determine the consistency of the wind measurements obtained prove useful in determining estimates of the wind errors.

Disturbance in the propagation of the signals from the navaid network transmitters is another source of error.

Passi and Morel (1987) performed an early study on LORAN wind errors. Commercially available systems could produce wind data of good quality, as illustrated in Table 13.6. The measurement quality obtained when working with mainly ground-wave signals was derived from installation tests in the British Isles as reported by Nash and Oakley (1992). The measurement quality obtained when working with transmitters at longer ranges, where sky waves are significant, was estimated from the results of Phase IV of the WMO International Radiosonde Comparison in Japan (see WMO, 1996). In the United Kingdom, LORAN-C windfinding was discontinued because of uncertainty about the future of LORAN-C in north-west Europe and was replaced by GPS windfinding at all operational sites.

Table 13.6. Random error (k = 2) and systematic bias expected from LORAN-C navaid windfinding systems in areas where the coverage is close to optimum

System	*Averaging time (s)*	*Systematic bias (m s^{-1})*	*Random error (m s^{-1})*
LORAN-C (ground wave)	30 – 60	Up to ±0.2	0.6 – 3
LORAN-C (sky wave)	60 – 120	Up to ±0.2	1.6 – 4

13.5.6 **Representativeness errors**

Most modern radiowind measurements observe small-scale variations in wind in the atmosphere which are not represented in current numerical weather prediction models. Thus, for instance, when GPS wind component profiles are compared directly with numerical model output from global models, the standard deviation of observation/numerical model output ($k = 2$) in mid-latitudes is usually between 4 and 6 m s^{-1} in the lower troposphere, and between 4 and 9 m s^{-1} in the upper troposphere, that is, it is always much larger than the instrumental vector errors quoted in Table 13.5 for a vertical resolution of 300 m. Some of this discrepancy will result from the poor accuracy of the reported winds as noted earlier in section 13.1.3.2.

Root-mean-square vector differences between radiosonde upper-wind measurements 2, 6, 18 and 54 h apart have been computed from the time series of measurements produced in the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China (WMO, 2011*b*), applying the technique used by Kitchen (1989). The results are shown as a function of height in Figure 13.4.

The RMS vector error in wind can then be expected to relate to time separation using the relationship, after Kitchen (1989):

$$\left(\tau_{\rm V}\left(\Delta t\right)\right)^2 = \left(b_{\rm V}\Delta t^{\gamma}\right)^2 + \left(\tau_{\rm V(small\ scale)}\left(\Delta t\right)\right)^2 \tag{13.5}$$

where $\tau_V(\Delta t)$ is the RMS vector difference between wind measurements separated by the time separation Δt; and $b_V \Delta t^{\gamma}$ is the structure function representing the RMS deviation due to synoptic scale and mesoscale changes with time, with b_V a constant and γ a constant. In Yangjiang, γ had a value of between 0.5 and 0.6 for wind measurements in the troposphere at time separations between 6 and 54 h. Finally, $\tau_{V(\text{small scale})}$ (Δt) is the RMS vector difference in upper wind from small-scale structures, such as quasi-inertial gravity waves, turbulent layers or cloud-scale structure.

In the troposphere in Yangjiang, the small-scale structure RMS vector difference was about 2 m s^{-1} ± 0.5 m s^{-1}, while the synoptic and mesoscale RMS vector difference was between

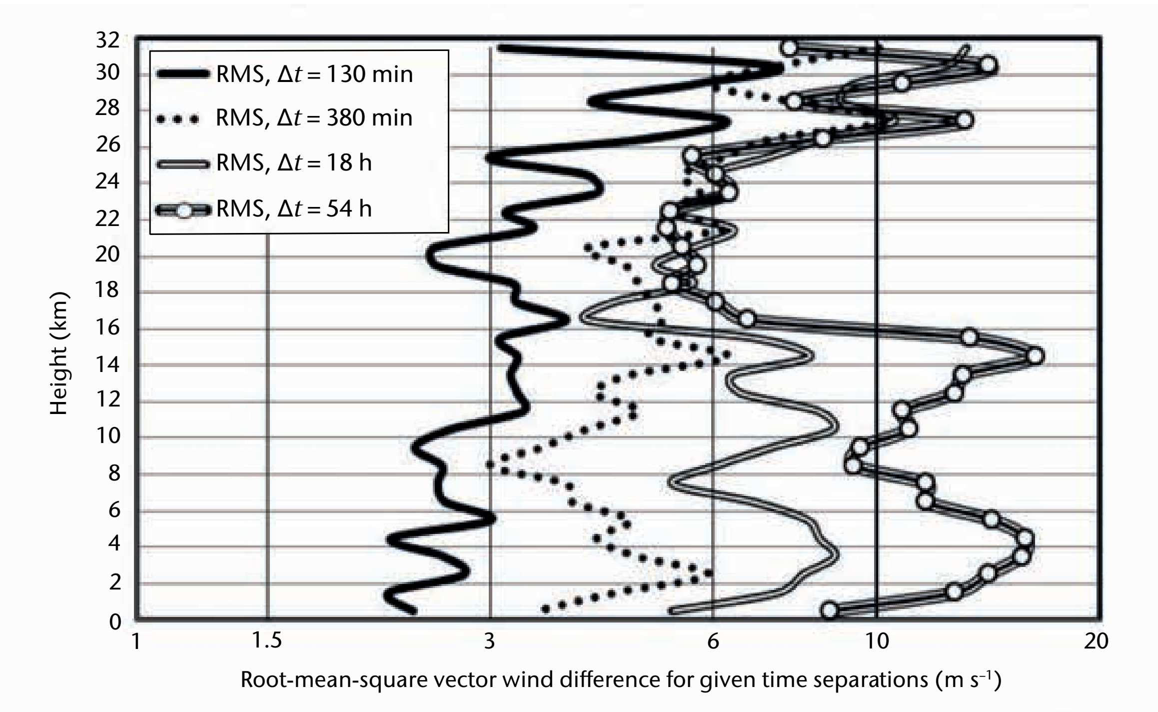


Figure 13.4. Root-mean-square vector wind differences ($k = 1$) for time separations of 2, 6, 18 and 54 h for 11 pairs of observations, with vertical resolution of 1 km, from the WMO Intercomparison of High Quality Radiosonde Systems in Yangjiang, China, in July 2010. The contributions from instrumental error have been removed from the differences.

2 and 3 m s^{-1} at a time separation of 2 h, increasing to about 7 m s^{-1} at a time separation of 18 h. These values are of similar magnitude to the values found by Kitchen (1989) in the lower and middle troposphere in the United Kingdom. The RMS vector differences were higher in the upper troposphere in the United Kingdom because of the synoptic scale variations associated with mid-latitude jet streams. Whereas the synoptic and mesoscale vector difference might be expected to fall to lower than 1 m s^{-1} at a time separation of 40 min in Yangjiang, there is no information on the time separations necessary to reduce the small-scale RMS vector difference to a value less than 1 m s^{-1}. This is why, to get close agreement between wind measurements, or for the measurement to represent the conditions in the atmosphere at a given time with high accuracy, the measurement needs to be performed at a time separation much lower than 20 min, as stated in section 13.1.3.3.

In Yangjiang, the small-scale fluctuations associated with quasi-inertial gravity waves dominate the variation of RMS vector difference with time, and it is not possible to fit a structure function for synoptic and mesoscale variation with time, as was also found in the United Kingdom in summertime conditions by Kitchen. The RMS vector differences at 18-hour time separation in Yangjiang were in the range 5 to 9 m s^{-1}, values of similar magnitude to those found in the United Kingdom.

Thus, representativeness errors in the winds will normally be most influenced by the small-scale variations, with synoptic and mesoscale variations most likely to be significant in association with the structures found with jet streams in the upper troposphere and lower stratosphere. As a result, there will be variation between different sites, and the values discussed here are only a snapshot of one type of location and synoptic condition, which did include measurements with typhoons approaching and leaving the area.

13.6 COMPARISON, CALIBRATION AND MAINTENANCE

13.6.1 Comparison

Upper-wind systems are usually fairly complex, with a number of different failure modes. It is not uncommon for the systems to suffer a partial failure, while still producing a vertical wind structure that appears plausible to the operators. Many of the systems need careful alignment and maintenance to maintain tracking accuracy.

The wind measurement accuracy of operational systems can be checked by reference to observation monitoring statistics produced by numerical weather prediction centres. The monitoring statistics consist of summaries of the differences between the upper-wind measurements from each site and the short-term forecast (background) fields for the same location. With current data assimilation and analysis techniques, observation errors influence the meteorological analysis fields to some extent. Thus, it has been shown that observation errors are detected most reliably by using a short-term forecast from an analysis performed 6 h before the observation time.

The performance of upper-wind systems can also be compared with other systems of known measurement quality in special tests. These tests can allow tracking errors to be evaluated independently of height assignment errors.

Both types of comparisons may be interpreted using the statistical methods proposed in WMO (1989).

13.6.1.1 *Operational monitoring by comparison with forecast fields*

The statistics for daily comparisons between operational wind measurements and short-term forecast fields of numerical weather prediction models can be made available to system operators through the lead centres designated by the WMO Commission for Basic Systems.

Interpretation of the monitoring statistics for upper winds is not straightforward. The random errors in the forecast fields are of similar magnitude or larger than those in the upper-wind system if it is functioning correctly. The forecast errors vary with geographical location, and guidance for their interpretation from the numerical weather prediction centre may be necessary. However, it is relatively easy to identify upper-wind systems where the random errors are much larger than normal. In recent years, about 6% of the upper-wind systems in the global network have been identified as faulty. The system types associated with faulty performance have mainly been radiotheodolites and secondary radar systems.

Summaries of systematic biases between observations and forecast fields over several months or for a whole year are also helpful in identifying systematic biases in wind speed and wind direction for a given system. Small misalignments of the tracking aerials of radiotheodolites or radars are a relatively common fault.

13.6.1.2 *Comparison with other windfinding systems*

Special comparison tests between upper-wind systems have provided a large amount of information on the actual performance of the various upper-wind systems in use worldwide. In these tests, a variety of targets are suspended from a single balloon and tracked simultaneously by a variety of ground systems. The timing of the wind reports from the various ground stations is synchronized to better than 1 s. The wind measurements can then be compared as a function of time into flight, and the heights assigned to the winds can also be compared independently. The interpretation of the comparison results will be more reliable if at least one of the upper-wind systems produces high-accuracy wind measurements with established error characteristics.

A comprehensive series of comparison tests was performed between 1984 and 1993 as part of the WMO International Radiosonde Comparison. Phases I and II of the tests were performed in the United Kingdom and United States, respectively (WMO, 1987). Phase III was performed by the Russian Federation at a site in Kazakhstan (WMO, 1991), and Phase IV was performed in Japan (WMO, 1996). Further tests in Brazil in 2001 (WMO, 2006*a*) were performed specifically to identify problems in GPS windfinding in the tropics, and this led to improved GPS radiosonde systems which were also tested in Mauritius in 2005 (WMO, 2006*b*) and most comprehensively in Yangjiang, China in 2010 (WMO, 2011*b*).

The information in Tables 13.4, 13.5 and 13.6 was primarily based on results from the WMO International Radiosonde Comparison and additional tests performed to the same standard as the WMO tests.

Now that the development of GPS windfinding systems is mature, most of these systems can be used as reliable travelling standards for upper-wind comparison tests in more remote areas of the world.

13.6.2 **Calibration**

The calibration of slant range should be checked for radars using signal returns from a distant object whose location is accurately known. Azimuth should also be checked in a similar fashion.

The orientation of the tracking aerials of radiotheodolites or radars should be checked regularly by comparing the readings taken with an optical theodolite. If the mean differences between the theodolite and radar observations of elevation exceed 0.1°, the adjustment of the tracking aerial should be checked. When checking azimuth using a compass, the conversion from geomagnetic north to geographical north must be performed accurately.

With navaid systems, it is important to check that the ground system location is accurately recorded in the ground system computer. The navaid tracking system needs to be configured correctly according to the manufacturer’s instructions and should be in stable operation prior to the radiosonde launch.

13.6.3 **Maintenance**

Radiotheodolites and radars are relatively complex and usually require maintenance by an experienced technician. The technician will need to cope with both electrical and mechanical maintenance and repair tasks. The level of skill and frequency of maintenance required will vary with the system design. Some modern radiotheodolites have been engineered to improve mechanical reliability compared with the earlier types in use. The cost and feasibility of maintenance support must be considered important factors when choosing the type of upper-wind system to be used.

Electrical faults in most modern navaid tracking systems are repaired by the replacement of faulty modules. Such modules would include, for instance, the radiosonde receivers or navaid tracker systems. There are usually no moving parts in the navaid ground system and mechanical maintenance is negligible, though antenna systems, cables and connectors should be regularly inspected for corrosion and other weathering effects. Provided that sufficient spare modules are purchased with the system, maintenance costs can be minimal.

13.7 **CORRECTIONS**

When radiowind observations are produced by a radar system, the radar tracking information is used to compute the height assigned to the wind measurements. These radar heights need to be corrected for the curvature of the Earth using the following:

$$\Delta z_{\text{curvature}} = 0.5\left(r_s \cdot \cos\theta\right)^2 / \left(R_c + r_s \sin\theta\right) \tag{13.6}$$

where r_s is the slant range to the target; θ is the elevation angle to the target; and R_c is the radius of the Earth curvature at the ground station.

In addition, the direction of propagation of the radar beam changes since the refractive index of air decreases on average with height, as temperature and water vapour also decrease with height. The changes in refractive index cause the radar wave to curve back towards the Earth. Thus, atmospheric refraction usually causes the elevation angle observed at the radar to be larger than the true geometric elevation of the target.

Typical magnitudes of refraction corrections, $\Delta z_{\text{refraction}}$, are shown in Table 13.7. These were computed by Hooper (1986). With recent increases in available processing power for ground system computers, algorithms for computing refractive index corrections are more readily available for applications with high-precision tracking radars. The corrections in Table 13.7 were computed from five-year climatological averages of temperature and water vapour for a variety of locations. On days when refraction errors are largest, the correction required could be larger than the climatological averages in Table 13.7 by up to 30% at some locations.

Table 13.7. Examples of corrections to radar height observations for Earth curvature and typical refraction

Plan range (km)	*Altitude (km)*	$\Delta z_{curvature}$	$\Delta z_{refraction}$ *60°N 01°W*	$\Delta z_{refraction}$ *36°N 14°E*	$\Delta z_{refraction}$ *1°S 73°E*
25	10	49	–9	–10	–12
50	15	196	–31	–34	–39
100	20	783	–106	–117	–133
150	25	1 760	–211	–231	–262
200	30	3 126	–334	–363	–427

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