CHAPTER 13 — MEASUREMENT OF UPPER WIND

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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, 1981):

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 speed and direction in the atmosphere.

This chapter will deal primarily with the pilot-balloon and radiowind 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.

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. 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. A more accurate wind direction report, as possible with BUFR code, must be used when the highest accuracy is required.

The geopotential unit used to assign the location in the vertical of upper air observations is the standard geopotential metre (symbol: m). This is defined as 0.980 665 dynamic metres. In the troposphere, the value of geopotential height is a close approximation to the height expressed in metres. 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.

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 and at all latitudes, and are usually used in conjunction with measurements of mass field (temperature and relative humidity). They are vital to the safety and economy of aircraft operations. Uncertainties in upper winds are the limiting factor in the accuracy of modern artillery and are, therefore, important for safety in military operations. Accurate upper winds and vertical wind shear measurements are critical for the launching of space vehicles and other types of rocket. In the boundary layer, upper winds with reliable measurements of vertical wind shear are essential for environmental pollution forecasting.

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 will not necessarily be input at standard pressures or heights, but will often be centred at pressure heights that vary as the surface pressure changes at the location of the observation. Thus, it is important 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 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. However, the advent of cheap computing systems has ensured that all the detailed structure relevant to meteorological operations and scientific research can be processed and reported. The upper-wind reports should contain enough information to define the vertical wind shears 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-X Ext. TEMP code or the FM 32-IX PILOT code (WMO, 1995), 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 that are larger than the observational errors. On occasion, the coding procedure may also degrade the accuracy outside the accuracy requirements in Chapter 12. This can be avoided by a variety of methods. 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. Reports submitted by using a suitable BUFR code could eliminate the current necessity of choosing significant levels.

13.1.3.3 ACCURACY REQUIREMENTS

Accuracy requirements for upper-wind measurements are presented in terms of wind speed and direction in Chapter 12, Annex 12.A. A summary of performance limits for upper-wind measurements in terms of standard vector errors is found in Chapter 12, Annex 12.B, Table 1. In addition, 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 practice, most well maintained operational windfinding systems provide upper winds with a standard vector error (2σ) that is greater 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 range of wind speeds likely to be encountered at various locations can also be found in Chapter 12, Annex 12.B, Table 1. Most upper-wind systems should be capable of measuring winds over a range from 0 to 100 m s^{-1}. Systems primarily used for winds at low levels may not need to cope with such a large range.

The vertical resolution quoted for upper-wind measurements in Chapter 12, Annex 12.B, Table 1 is 300 to 400 m in the troposphere and 600–800 m in the stratosphere. A higher vertical resolution (50–150 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.

In Chapter 12, Annex 12.A, the most stringent requirements for upper-wind measurements are associated with observations of mesoscale atmospheric motions. In addition, very high accuracy upper-wind measurements are often specified for range operations such as rocket launches. 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 rms 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 are 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 less than about 10 min in time.

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 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 are used. If this is the case, then national technical infrastructure must be able to provide adequate maintenance for the variety of systems deployed.

13.1.4 *Methods of measurement*

Upper winds are mainly acquired by using rawinsonde techniques, although pilot balloon and radiowind observations may be used when additional upper winds 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 profiler, and doppler weather radars. 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 light detection and ranging (lidars) and radars are expected to improve the global coverage of the current observing systems. Sound detection and ranging (sodars), 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.

The 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. As the horizontal motion of the air is to be measured, the target that is 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 measures of its plan position or, alternatively, its horizontal velocity at known time intervals.

The accuracy requirements in 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 A DIRECTIONAL AERIAL

The ground system tracks the target with a directional aerial measuring azimuth plus any two of the following parameters: elevation angle, slant range, and height. Measurements can be achieved using a primary radar to track a reflecting target carried by the balloon, a radiotheodolite or secondary radar tracking a radiosonde carried by a balloon, or an optical theodolite tracking a balloon. 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.

Radiotheodolite systems are best suited for upper-wind measurements when balloon elevations stay above 10–15°. Primary radars require skilled staff for successful maintenance and have higher initial capital costs. However, primary radars do allow cheap radiowind measurements when radiosonde measurements are not required. Primary radars can also satisfy very high accuracy requirements for upper wind in all conditions. Secondary radar systems are a possible alternative when available from a suitable manufacturer, but successful operation may require too wide a radiofrequency spectrum in the "Meteorological-Aids bands" to be practical in many countries.

The choice between using a primary radar or a radiotheodolite for upper-wind measurements will be partly influenced by the maximum slant range expected at the observation site. A primary radar system or navigational aid (navaid) windfinding system is essential for good measurement accuracy at the longer ranges. The maximum range varies considerably with latitude, with 70 km being adequate in equatorial and polar regions, but which 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.

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 (per cent)	5	2	1	0.5

13.1.4.2 TRACKING USING RADIONAVIGATIONAL SIGNALS

A radiosonde with the capability of receiving signals from a system of navigational radio transmitters is attached to a target (either ascending balloon or dropsonde parachute). The changes in either phase, as well as the Doppler shift, or time of arrival of the radionavigation signals received at the radiosonde are used to compute the horizontal motion of the target. The method using surface-based radio beacons, such as Omega (very low frequency (VLF)) and Loran, is described in WMO (1985). Radiosonde manufacturers have been offering radiosondes with satellite-based global positioning system (GPS) since 1995 (WMO, 1994 and Kaisti, 1995), but they have not yet achieved the necessary reliability for operation.

The use of 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 amount of maintenance required by navaid ground equipment is also very low.

Navaid wind measurement accuracy using terrestrial transmitters depends on the geometry, phase, stability, and signal to noise ratio of the radionavigational signals available at a given location. The accuracy will not usually vary too much during flight as long as the reception of the navaid signals by the radiosonde and the reception of the navaid data transmitted from the radiosonde to the ground-processing system remain adequate. Navaid radiosondes often experience difficulties in receiving reliable navigation signals immediately after launch. This can impose a significant limitation on the operation of Omega (VLF) systems since they require several minutes of valid tracking data before acceptable winds can be derived. Thus, Omega systems may not be able to meet stringent accuracy requirements in the boundary layer.

The quality of navaid measurements may degrade if upper winds are very strong and if reception from the radiosonde by the ground system becomes poor. The build up of electrostatic charge on the radiosonde navaid aerial during thunderstorms or charged ice clouds often causes long periods of signal loss during flights using Omega (VLF) and Loran navaid systems. The static on the radiosonde aerial will normally discharge later in the flight when satisfactory measurements will again become possible.

13.2 Sensors and instruments for upper wind

13.2.1 *Optical theodolite*

Optical theodolites may be used for tracking balloons when the expense of radiowind measurements is not justified. Operators need significant training and skill if upper-wind measurement errors are not to increase rapidly as the balloon ascends above the boundary layer.

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 not 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 divisions not 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 as to permit reading 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, not 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.

13.2.2 *Radiowind systems in general*

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.

13.2.3 *Radiotheodolite*

Radiotheodolite windfinding is best suited for 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 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 Chapter 12 with a radiotheodolite if upper winds are consistently very strong, unless a transponder is used to provide a measurement of slant range (see section 13.2.4.2).

A radiotheodolite will usually 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 radiofrequency employed is usually 1 680 MHz. A good aerial design with a diameter of about 2 m should have low sensitivity in its sidelobes 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.

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 multipath interference conditions change as the radiosonde moves; this can lead to large systematic wind errors (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 satisfactory, a suitable upper-wind report can be issued to the users.

Balloons will sometimes reverse direction depending on surface winds and fly back over the radiotheodolite shortly after launch even though the balloon is launched upward of 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 position 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 expected to be more reliable in service and, thus, cheaper to maintain.

13.2.4 *Radar*

The essential feature of the radar tracking technique compared to the radiotheodolite 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 in Chapter 12 can be met in almost all circumstances. Very high accuracy specifications for upper winds can be met with high precision tracking radars. For measurement accuracy better than about 1 m s^{-1} it is essential to use balloons with sculptured surfaces (very expensive) rather than standard meteorological balloons.

A radiosonde does not have to be used in order to generate winds with a primary radar. Substantial savings from minimizing expenditure on radiosondes are possible as long as the technical support structure to maintain the radar exists and staff costs are very low. However, in many countries, the high costs of replacing and operating radars when compared to the costs of navaid windfinding systems have led to a decreasing use of primary radar systems for routine meteorological operations.

Most windfinding radar systems comprise a modulator, a radiofrequency oscillator, a direction finding aerial system, a receiver, and a data-processing unit to supply slant range, azimuth, and elevation to a ground system computer. The modulator produces sharp voltage pulses of about 1 μs duration at a rate usually of between 400 and 1 000 pulses per second. These pulses drive a magnetron, causing it to produce bursts of power of several hundred kilowatts, at ultra-high frequency. This energy is transmitted through a wave-guide to the focus of a paraboloidal reflector. When the latter is directed towards the balloon target, pulses are reflected back to the same aerial system and converted by the receiver. The time interval between the emission of the pulse by the magnetron and the reception of the signal back from the balloon target is measured. This is converted into slant range to the target after compensation for signal delays in the detection electronics.

Wavelengths of 3.2, 5.7 and 10.6 cm are used. Those of 3.2 cm allow a smaller aerial to be used for the desired tracking accuracy and, hence, the resultant radar tends to be cheaper. However, signal attenuation in heavy rainfall is much greater at 3.2 cm than at 10.6 cm. Where heavy rainfall is common, the longer wavelengths may have to be used to ensure all-weather observing capability to long ranges.

13.2.4.1 RADAR REFLECTORS

The most efficient form of target for the wavelengths indicated above is the corner reflector, consisting essentially of three mutually perpendicular electrically-conducting planes. In one design, the top plane — which is horizontal in flight — is a square. A model for longer ranges uses a three-gabled construction with provision to make the reflector rotate. This avoids the possibility of a "null" point lasting for any appreciable time in the target reflectivity observed by the radar. The weight and drag of the target during flight should be as small as possible. The target needs to be collapsible to facilitate storage and transport.

The energy intercepted by a corner in the radar beam is directly proportional to the square of the linear size of the reflector. General radar theory indicates that the ratio of energy received to the energy transmitted by the radar is directly proportional to the square of the reflector size and inversely proportional to the fourth power of the slant range from the radar to the reflector. The reflector used should be large enough to ensure accurate tracking to the largest ranges under the expected meteorological conditions. When upper winds are weak, smaller cheaper targets may be used.

The peformance of corner reflectors depends, to some extent, on the radar wavelength. Short-wavelength radars (3 cm) return more energy from a given target, making low-power systems practicable, but attenuation and immersion of the target in rain are more serious at short wavelengths.

Corner reflectors with an 0.5 to 1 m size are suitable for most applications. Here, the size is taken as the length of the outside (hypotenuse) of the triangles forming the corner reflectors. Metal foil glued to paper or expanded polystyrene, or metallized fabric net with a mesh size of about 0.5 cm, or metallized mylar have been successfully used to construct suitable conducting planes. These planes need to be good electrical conductors. For instance, planes with a resistance lower than 20 ohms between points 30 cm apart were found to give a satisfactory result. When the reflector is assembled, the target surfaces should be flat planes to within 0.6 cm and the planes should be perpendicular to within 1°.

13.2.4.2 TRANSPONDER SYSTEMS

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 can be 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.

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.

However, if significant numbers of radiowind measurements without simultaneous radiosonde measurements are required at a given location, the cost of operational consumables will be higher with a secondary radar than with a primary radar, and the primary radar may prove to be the most suitable choice.

The complexity of the system and the maintenance requirements of a secondary radar system usually fall between that of radiotheodolites and primary radars.

13.2.5 *Navigational aid tracking systems*

In navigational aid 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 primary purpose of the system will usually be the operational navigation of aircraft or ships or navigation in support of military purposes. The navaid systems currently used operationally for wind finding are the Omega and Loran systems using ground-based transmitters. The use of the satellite-based GPS is in an advanced stage of development.

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 the navaid 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 good line of sight to the radiosondes in all directions. The radiosonde radiofrequency design must also ensure that faulty modulation of the radiosonde carrier frequency with the navaid signals does not lead to break up the carrier frequency transmitted from the radiosonde to the station.

The accuracy of upper-wind measurements that can be achieved with navaid tracking will vary with the geographical location and navigational signals used. As long as sufficient signals are available to produce viable navigation, measurement accuracy should be similar to the range of accuracy available with radiotheodolites and radars.

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 the ground-based systems, 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 to the time stamping of the radiosonde height measurements.

13.2.5.1 AVAILABILITY OF NAVAID SIGNALS IN THE FUTURE

A major change in the availability of navaid signals is under way. 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. However, for various reasons, some countries have chosen to persist with 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.

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 and the windfinding system must be able to determine the satellite signals received and the position and movement of the satellites at any time. The GPS signals are of much higher radiofrequency than Omega or Loran-C. Thus, GPS signals must be pre-processed to a much higher degree on the radiosonde before transmission to the ground receiver. Hence, GPS radiosondes must incorporate a higher processing capability than has generally been used in radiosondes up to this time. However, it is expected that the resultant GPS wind measurement accuracy will be equivalent to, or better than, good primary radars.

13.2.5.2 VERY LOW FREQUENCY (VLF) OMEGA NETWORKS

The Omega navaid windfinding has found increasing use since the early 1980s for meteorological operations and research. However, the operators of this network have indicated that it will cease to function within a few years. The Russian Alpha navigation network operates at similar frequencies as Omega. There are also a limited number of additional regular VLF transmissions of sufficient stability that can also be exploited for wind measurements. Thus, following the closure of the Omega network, VLF windfinding might still be possible in some locations. The availability of the additional VLF signals on a daily routine basis over a number of years would have to be assured before investing in equipment that could utilize the additional VLF signals.

Omega is a network of eight transmitters controlled by atomic clocks and operating at a very low frequency band. The system provides near global coverage, but in very limited regions of the globe (such as parts of Antarctica) signals are not adequate for regular accurate wind measurements. Each station transmits sequentially for 0.9 to 1.2 s on four assigned frequencies of 10.2, 11.05, 11.33, and 13.6 kHz, with an additional frequency characteristic of the given station. The stations do not transmit simultaneously on any frequency, nor does a station transmit on more than one frequency at a time. The cycle is repeated every 10 s.

At the chosen frequencies (wavelengths 22 to 30 km) the ionosphere and Earth's surface act as a waveguide. The VLF and Omega transmitters excite various modes of propagation whose amplitudes and phase velocities vary with the height of the ionosphere, direction of propagation, and range from the transmitter. As a result of the presence of many high order modes, the signal phase is difficult to predict and exploit within about 1 000 km of a transmitter. Beyond this range, the phase is a useful linear function of distance. The height of the ionosphere has a diurnal variation. This produces variations in phase received at a given location from a stationary transmitter, especially if either sunset or sunrise is occurring along most of the path from the transmitter to the receiver. Sporadic signal propagation anomalies occur when the ionosphere is disturbed by X-rays and particle fluxes from the Sun, with the most frequent problems linked towards the end of the 11-year cycle in sunspot activity.

The Omega signals received by the radiosonde Omega aerial are used to modulate the radiosonde carrier frequency. The Omega signals are then stripped from the carrier after reception by the radiosonde receiver and fed to the Omega tracker in the ground system. In the Omega tracker, analogue filtering must precede the phase detection in order to limit the incoming bandwidths and to clip high amplitude peaks of noise. As the filter circuits tend to oscillate after an energetic disturbance (caused by lightning) complementary digital filtering is necessary. The phase detector may exploit Fourier transformation and cross-correlation techniques.

The rates of change of phase of the Omega signals received by the radiosondes are computed relative to an internal reference signal. When using standard hyperbolic computations, the required stability of the reference is only moderate, and a high-quality crystal oscillator proves satisfactory.

13.2.5.3 LORAN-C CHAINS

The Loran-C system is a relatively high accuracy long range navigational aid operating in the low frequency band centred on 100 kHz (wavelength 3 km). As its primary purpose was for marine navigation, particularly in coastal and continental shelf areas, Loran-C coverage was only provided in certain parts of the world. These were mostly in maritime areas of the northern hemisphere. In recent years, ownership of most of the transmitters outside the coastal areas of North America has either changed hands or the stations have been closed. Some of the chains have been refurbished under new ownership to provide regional marine navigational networks. In North America, the future of the Loran-C chains is uncertain although current commitments would sustain operations until about the year 2000.

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 ms.

The Loran-C signals propagate both as ground and sky waves reflected from the ionosphere. The ground waves are much more stable in propagation than the Omega signals. 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 are 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. In the best situations, Loran-C winds can be much more accurate and of higher vertical resolution than Omega winds.

As with Omega radiosondes, 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.

Loran-C windfinding systems have been used extensively for meteorological research in North America and Europe and for meteorological operations in north-west Europe. Changes in Loran-C chain configurations as transmitter systems have been refurbished have highlighted the requirement that the operational Loran trackers used should be able to adapt to new chain configurations through software adjustments rather than through hardware replacement.

13.2.5.4 GLOBAL POSITIONING SYSTEM (GPS)

The global positioning system (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 hours and 58 minutes. 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 (C/A) 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 C/A spectrum width to 2 MHz;

(*b*) The precision (P) code, may be replaced by a military controlled Y code during periods when anti-spoofing (AS) is active. The P 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 Omega and Loran. The much smaller aerial used for receiving the GPS signals has to be 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 Omega and Loran aerials. However, the siting of the GPS aerial may cause a conflict with siting of the temperature sensor on the radiosonde. The temperature sensor also needs to be held above the top of the radiosonde body. (This is to prevent problems in daylight when air heated from flowing over the top of the radiosonde body can then flow over the temperature sensor if it is not held above the top of the radiosonde body).

The bandwidth of the ranging codes is too wide for the GPS signals to be retransmitted to the ground station from the radiosonde in the manner used for Omega and Loran signals. 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 Omega and Loran, or as a digital data stream). The pre-processing can be achieved by a variety of techniques that are under development. Successful radiosonde GPS processors will have to be cheap to be manufactured in large numbers.

The first practical radiosonde GPS systems that have been developed use the C/A 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. The satellite almanac and other GPS information are stored in the ground station GPS processor. Accurate wind computations require signals from a minimum of four satellites. In a differential mode, the phase or doppler shift 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 AS 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 compared to Omega or Loran. Thus, it is possible to measure the modulation of apparent horizontal velocity since the radiosonde swings as a pendulum under the balloon during a period of about 10 s. Upper winds at a very high vertical resolution (50 m) are not required for most purposes, except in the atmospheric boundary layer, and the swinging motions are best filtered out before the upper winds are reported.

Early GPS radiosonde prototypes were quite susceptible to external radiofrequency interference, since the radiosonde navaid receiver sensitivity was designed to be adequate for the weak GPS signal strengths. In the future, radiosondes will probably have to share radiofrequency spectrum with increasing numbers of other users. Thus, it is important that protection against external radiofrequency interference should be optimized by the radiosonde design.

The practical utility and limitations of GPS radiosondes in operational use will become apparent once the production of the radiosondes has been achieved in large numbers. It is expected that GPS radiosondes will prove as easy to operate as the other navaid systems, while providing better measurement accuracy under most circumstances.

13.3 Methods of measurement

13.3.1 *General considerations concerning data processing*

Modern tracking sensors can take readings much more frequently than at the one-minute 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 prior to issuing the information to users.

Thus, sampling of tracking data is best made at intervals of 10 s or less. Sampling should be at the highest rate that is 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, then 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 to be 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, then 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 this circumstance.

It has been suggested that upper-wind systems should use more than one tracking method to improve the quality assurance of the observations. In this circumstance, an optimum solution of the positional information could be found through the least-squares method applied on the over-determined system of nonlinear equations (see Lange, 1988 and Passi, 1978). This type of analysis could also be applied for the interpretation of tests where a balloon is tracked simultaneously by more than one system.

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 made at intervals of not less than one minute. 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 ringing 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 a pocket calculator.

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 and 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 can 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 can be checked against known stationary targets, if suitable targets exist. The tracking of the radar in general can 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.

At heights up to about 24 km, the comparison of radar height measurements with radiosonde geopotential heights can be used to identify radar tracking which fail 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 radiosonde geopotential height were established for the most widely used radiosondes by WMO (1987).

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 sidelobe of the aerial may be strong enough to sustain automated tracking at short ranges. However, when tracking on a sidelobe, 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 boresight, 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 radionavigational systems*

The following text applies to the ground-based navaid systems which are still the only fully navaid windfinding operational systems, but the same principles apply to the satellite-based GPS system currently being developed.

In order to derive satisfactory upper-wind measurements, it is necessary for the radiosonde to receive signals from at least three 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 it 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 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).

If only three signals are available at a given site, the purchase of a navaid tracking system for research purposes may be acceptable, but for continuous meteorological operations this would be extremely risky. Most transmitters are closed down for maintenance during a year and, during this time, it will be impossible to obtain upper-wind measurements.

The computer software used for navaid wind processing must be sophisticated enough to deal with the various navaid signal anomalies that occur (see Lange, 1983 and Olson, 1979).

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 must also provide clear indications to the operator of the navaid signals available for windfinding prior to launch and also during the radiosonde flight.

Once launched, the navaid windfinding systems are highly automated. However, estimates of the expected measurement errors based on the configuration and quality of 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 that are clearly providing below standard observations. These observations need to be suppressed and a re-flight attempted, where necessary.

13.4 Exposure of ground equipment

The site for a radiotheodolite or radar should be 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 1°- or 2°-elevation. This would cut out ground returns, except at very short ranges.

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 for successful navaid measurements. These aerials will require mounting 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 measurement. 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. If the upper-wind measurement is required to detect a localized effect influencing an airfield, then 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 errors in tracking 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 manual computation of winds 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 upperwind 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, 1995).

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 lower vertical resolution. For much of the time, upper winds do not change very rapidly in the vertical. It is often difficult to find any large difference between an upper-wind measurement made at an 150 m vertical resolution and a measurement made at a 1.2 km vertical resolution. Omega windfinding systems have mostly been used at a 1.2 km vertical resolution, a vertical resolution less than ideal when compared to many of the requirements in Chapter 12. However, Omega windfinding systems have been considered acceptable as operational systems, although they are not suitable for use in applications where accurate measurements of vertical wind shear are essential.

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 are not usually significant unless the height is derived from time into flight and an assumed rate of ascent for the balloon.

However, testing of fully automated upper-wind systems has often revealed discrepancies between the times assigned to wind observations and those assigned to the associated radiosonde measurements. In some cases, the wind timing was not initiated at the same time as that of the radiosonde, in others synchronization was lost during flight for a variety of reasons. In several other systems, the times assigned to the reported winds were not 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 in reliable operational systems.

13.5.1.3 TARGET MOTION RELATIVE TO THE ATMOSPHERE

The motion of the target relative to the air will be most significant 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 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 of 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 Schaeffer 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:

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

$$\varepsilon_v^2 = 2 \cdot [\varepsilon_r^2 \cdot Q^2/(Q^2 + 1) + \varepsilon_\theta^2 \cdot h^2 + \varepsilon_\varphi^2 \cdot h^2 \cdot Q^2]/t^2 \tag{13.1}$$

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

$$\varepsilon_v^2 = 2 \cdot [\varepsilon_h^2 \cdot Q^2 + \varepsilon_\theta^2 \cdot h^2 \cdot (Q^2 + 1)^2 + \varepsilon_\varphi^2 \cdot h^2 \cdot Q^2]/t^2 \tag{13.2}$$

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; t 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 5 to 8 m s^{-1}. The vector wind error values are derived from equations 13.1 and 13.2 for various heights and values of Q, for a system tracking with the following characteristics: ε_r 20 metres; ε_θ 0.1 degree; ε_φ 0.1 degree; ε_h height error equivalent to a pressure error of 1 hPa; t 1 minute.

Table 13.2 demonstrates that measurements with a radiotheodolite (or optical) 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 13.1 and 13.2, 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 system, 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 and the ratios become very much

TABLE 13.2
90 per cent 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 *at 5 km*	ε_v *at 10 km*	ε_v *at 15 km*	ε_v *at 20 km*	ε_v *at 25 km*	ε_v *at 30 km*	ε_v *at 5 km*	ε_v *at 10 km*	ε_v *at 15 km*	ε_v *at 20 km*	ε_v *at 25 km*	ε_v *at 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: (1) 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.

(2) 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
($\alpha_{\varepsilon v}$ = tangential error/radial error)

	Radar						*Radiotheodolite*					
Q	$\alpha_{\varepsilon v}$, *5 km*	$\alpha_{\varepsilon v}$, *10 km*	$\alpha_{\varepsilon v}$, *15 km*	$\alpha_{\varepsilon v}$, *20 km*	$\alpha_{\varepsilon v}$, *25 km*	$\alpha_{\varepsilon v}$, *30 km*	a_{ev}, *5 km*	$\alpha_{\varepsilon v}$, *10 km*	$\alpha_{\varepsilon v}$, *15 km*	$\alpha_{\varepsilon v}$, *20 km*	$\alpha_{\varepsilon v}$, *25 km*	$\alpha_{\varepsilon v}$, *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	2	3	4	4	5	5	1/5	1/5	1/6	1/6	1/7	1/14
7	3	5	6	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

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 system. 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 possible 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 Radiosonde Comparison (see section 13.6.1.2 for references on the tests).

Of the three radiotheodolites tested in the WMO 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 jetstreams. The smaller portable radiotheodolite deployed by 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.

TABLE 13.4

Estimates of the typical random vector errors (2σ level, unit: m s^{-1}) in upper-wind measurements obtained during the WMO Radiosonde Comparison
(estimates of typical values of Q and $\alpha_{\varepsilon v}$ for each of the four phases are included)

System	*ε_v at 3 km*	*$\alpha_{\varepsilon v}$, 3 km*	*Q 3 km*	*ε_v at 18 km*	*$\alpha_{\varepsilon v}$, 18 km*	*Q 18 km*	*ε_v at 28 km*	*$\alpha_{\varepsilon v}$, 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*
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	Republic of 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, Russia]	1.5	≈1	<1	2.6	≈1	3	2.6	≈1	1.5	Republic of Kazakhstan
Secondary radar [China]	1.5	≈1	<1	3.8	≈1	3	3.4	≈1	1.5	Republic of Kazakhstan

* Data obtained in the United Kingdom test following Phase I of the WMO Radiosonde Comparison (see Edge, *et al.*, 1986).

13.5.4 *Errors in ground-based radionavigational 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 that is similar to or less than the increase in the range for a primary radar. Signal reception from a radiosonde immediately after launch is not always reliable. Omega and Loran-C winds have larger errors immediately after launch than when the radiosonde has settled down to a stable motion several minutes into flight.

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 2.5 to 4 min with Omega signals, from 30 s to 2 min for Loran-C signals and less than a minute for GPS signals. Signal strength received at a given location from some Omega or Loran-C transmitter 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 the signal strength. The fluctuations in signal strength and stability can be so large that, in some locations, successful wind measurement with Omega or Loran-C may not be possible at all times of the day.

A second major influence on 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. Diurnal effects in the propagation of Omega signals can produce systematic errors as large as 1 m s^{-1} in the direction of the path between the radiosonde and the transmitter affected by the anomalous phase changes. This effect can be seen in Omega measurements performed at 1800 and 0600 UTC in Phase III of the WMO Radiosonde Comparison (WMO, 1991). At 1800, Omega winds had a mean difference of –1 m s^{-1} relative to the Russian secondary radar measurements of the westerly wind component, but at 0600, the mean difference between the two systems was 0.4 m s^{-1}. In contrast, westerly wind components measured by a United States radiotheodolite had differences of 0.1 and 0.2 m s^{-1} from the secondary radar for the same times.

13.5.4.1 OMEGA WINDFINDING SYSTEMS

As noted above, the propagation of Omega navaid signals varies with time of day. Also, Omega signals suffer large attenuation over ice and, to a lesser extent, over dry land. The lowest attenuation occurs over sea paths. Some areas of the world have a high redundancy in available Omega signals for navigation, while in some areas, navigation is barely possible. Subsequently, the accuracy of Omega windfinding systems varies in different parts of the world and at different times of the day, year, and solar cycle (see for instance Franklin and Julian, 1985).

The best Omega windfinding systems utilize as many of the different Omega frequencies as possible with as many station signals as possible (after excluding signals from stations whose direction of arrival cannot be identified unambiguously). Systems that only select a minimum of three stations for tracking provide much poorer wind measurement accuracy. The values for Omega errors in Table 13.5 are estimates for the better Omega windfinding systems based on a survey of the results from the WMO Radiosonde Comparison (see section 13.6.1).

13.5.4.2 LORAN-C WINDFINDING SYSTEMS

In some areas of the world, Loran-C navaid windfinding systems are able to produce more accurate measurements than Omega radiosondes at higher resolution. This situation was reviewed in Passi and Morel (1987). Commercially available systems produce winds of good quality as indicated in Table 13.5. The measurement quality obtained when working with mainly groundwave 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 Radiosonde Comparison in Japan (see WMO, 1996).

13.5.5 *Errors in the global positioning system (GPS) windfinding systems*

In theory, GPS windfinding systems using C/A ranging codes in a differential mode should be capable of measuring winds to an accuracy of 0.2 m s^{-1}. The estimates of accuracy in Table 13.5 were made on the basis of tests performed in early 1996 with pre-production radiosondes (Elms and Nash, 1996). The best GPS wind accuracy was only achieved in the lower troposphere, and accuracy decreased at upper levels to values slightly poorer than for Loran-C winds. The degradation at upper levels may have been due to the limitations of the telemetry link to the ground. Alternatively, the differential navaid technique may not be able to compensate phase instabilities to the same extent, once the radiosonde moves significant distances away from the ground station and ascends into the stratosphere. Stickland (1996) found very good agreement with radars in some flights but very poor in others. Some of the poor results were due to software errors.

GPS wind measurements are expected to be at least as reliable as the best primary radar measurements in the long term.

13.6 Comparison, calibration, and maintenance

13.6.1 *Comparison*

Upper-wind systems are usually fairly complex systems 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

TABLE 13.5

Random error (2σ level) and systematic bias expected from navaid windfinding systems in areas where the coverage of navaid signals is close to optimum

System	*Averaging time (s)*	*Systematic bias (m s^{-1})*	*Random error (m s^{-1})*
Omega	150–240	up to ±1	2.5–5
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
GPS	5	up to ±0.1	0.4–2*

* Value taken from Elms and Nash, 1996.

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 six hours 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.

Interpretation of both types of comparison may be undertaken with 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 per cent 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 were performed between 1984 and 1993 as part of the WMO 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 Russia at a site in the Republic of Kazakhstan (WMO, 1991), and Phase IV was performed in Japan (WMO, 1996).

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

Once the development of GPS windfinding systems is complete, it is hoped that these systems will be useful 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°, then the adjustment of the tracking aerial should be checked. When checking azimuth by 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 from 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 to the earlier types in use. The cost and feasibility of maintenance support must be important factors in 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. As long as 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:

$$\Delta z_{curvature} = 0.5\,(r_s \cdot \cos\theta)^2 / (R_c + r_s \sin\theta) \qquad (13.3)$$

where r_s is the slant range to the target; θ is the elevation angle to the target; 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, $\Delta z_{refraction}$, can be seen in Table 13.6. These were computed by Hooper (1981). 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 13.6 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 13.6 by up to 30 per cent at some locations.

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TABLE 13.6

Examples of corrections for Earth curvature and refraction to observed radar height

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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