Can the speed and direction of wind be determined from the slant angle that rain drops make while falling?

http://answers.yahoo.com/question/index?qid=20070530161135AABArVu

What speed do raindrops fall at????????????????

Best Answer - Chosen by Asker

A number of people have quoted 32 feet/s or 9 m/s, referring to acceleration due to gravity. Acceleration measures change in speed and is measured in units of feet per second per second or meters per second per second. So this is not the same as the 'speed' at which the raindrops fall.

Neglecting effects due to wind, the raindrop will have two main forces acting on it - downward force due to gravity, upward force due to air resistance (or drag). Buoyancy can be neglected given that water is considerably more dense than air.

Air resistance increases with speed (proportional to square of velocity) so initially the rain drop will accelerate downward at something less that 'g' (acceleration due to gravity - 9.8 m/s/s).

As drag increases, the acceleration downward will decrease due to the opposing upward force of drag until a speed is reached at which the downward force of gravity is balanced by the upward drag.

Once the forces are balanced (and neglecting other effects like I said) there will be no more change in velocity - that's one of Newtons Laws of motion. The speed at which the rain drop is now moving downward is called terminal velocity.

Acceleration due to gravity is constant and independent of mass. As well as changing with velocity, drag depends on cross sectional area and a number of other properties. So larger drop will experience more drag and fall slower.

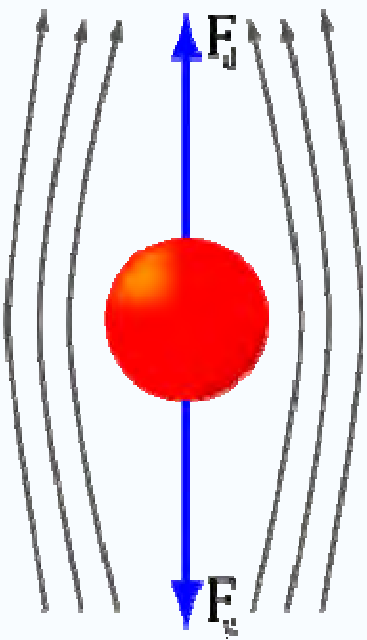
According to the wonderquest web site the range of terminal velocity for raindrops is roughly 2 m/s to 9 m/s (5 to 20 mph)

Hope that helps.

Source(s):
http://en.wikipedia.org/wiki/terminal_ve...

Terminal velocity

From Wikipedia, the free encyclopedia
Jump to: navigation, search
For other uses, see Terminal velocity (disambiguation).



An object reaches terminal velocity when the downward force of gravity equals the upward force of drag. The net force on the body is then zero, and the result is that the velocity of the object remains constant.

In physics, **terminal velocity** is the velocity at which the drag force of a falling object equals the weight of the object minus the buoyant force, which halts acceleration and causes speed to remain constant.

As an object accelerates downwards due to gravity, the drag produced by the passing through a fluid medium, (usually air), increases. At a particular speed, the drag force produced will be equal to the downward force, mostly the weight (mg), of the object. Eventually, it plummets at a constant speed called terminal velocity. Terminal velocity varies directly with the ratio of drag to mass. More drag means slower terminal velocity. Increased mass means higher terminal velocity. An object moving downwards at greater than terminal velocity (for example because it was affected by a force downward or it fell from a thinner part of the atmosphere or it changed shape) will slow until it reaches terminal velocity.

For example, the terminal velocity of a skydiver in a normal free-fall position with a closed parachute is about 195 km/h (120 mph or 54 m/s). This velocity is the asymptotic limiting value of the acceleration process, since the effective forces on the body more and more closely balance each other as it is approached. In this example, a speed of 50% of terminal velocity is reached after only about 3 seconds, while it takes 8 seconds to reach 90%, 15 seconds to reach 99% and so on.

Higher speeds can be attained if the skydiver pulls in his limbs (see also freeflying). In this case, the terminal velocity increases to about 320 km/h (200 mph or 89 m/s), which is also the maximum speed of the peregrine falcon diving down on its prey. Competition speed skydivers fly in the head down position reaching even higher speeds. Current world record is 614 km/h or 382 mph.

An object falling will fall 9.81 meters per second faster every second ($9.81\ m/s^2$). The reason an object reaches a terminal velocity is that the drag force resisting motion is directly proportional to the square of its speed. At low speeds the drag is much less than the gravitational force and so the object accelerates. As it speeds up the drag increases, until eventually it equals the weight. Drag also depends on the cross sectional area. This is why things with a large surface area such as parachutes have a lower terminal velocity than small objects like cannon balls.

Mathematically, terminal velocity is given by

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}}$$

see derivation

where

V_t is the terminal velocity,
m is the mass of the falling object,
g is gravitational acceleration at the Earth's surface,
C_d is the drag coefficient,
ρ is the density of the fluid the object is falling through, and
A is the object's cross-sectional area.

So it can be said that, on Earth, the terminal velocity of an object changes due to the properties of the fluid, mass and the cross sectional area of the object.

This equation is derived from the drag equation by setting drag equal to *mg*, the gravitational force on the object.

Note that the density increases with decreasing altitude, ca. 1% per 80 m (see barometric formula). Therefore, for every 160 m of falling, the "terminal" velocity decreases 1%. After reaching the local terminal velocity, while continuing the fall, speed *decreases* to change with the local terminal velocity.

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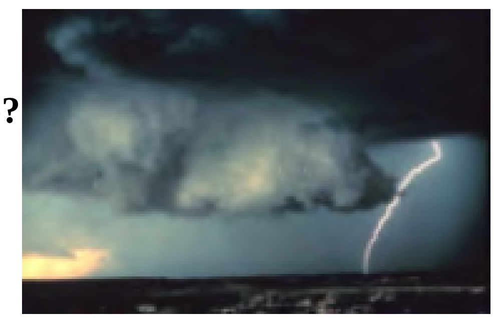
http://en.wikipedia.org/wiki/drag_coeffi...

http://www.wonderquest.com/falling-raind...

Falling raindrops hit 5 to 20 mph speeds



Q: What is the speed of a falling raindrop?
--Ed Rogers, Las Vegas Nevada

A: It depends on the size and weight of the raindrop how fast it falls: the heavier, the faster. At sea level, a large raindrop about 5 millimeters across (house-fly size) falls at the rate of 9 meters per second (20 miles per hour). Drizzle drops (less than 0.5 mm across, i.e., salt-grain size) fall at 2 meters per second (4.5 mph).

[NOAA] Storm

A raindrop starts falling and then picks up speed because of gravity. Simultaneously, the drag of the surrounding air slows the drop's fall. The two forces balance when the air resistance just equals the weight of the raindrop. Then the drop reaches its terminal velocity and falls at that speed until it hits the ground. This simple view neglects updrafts, downdrafts, and other complications.

The air resistance depends on the shape of the raindrop, the cross-sectional area presented to the airflow, and the raindrop's speed. Most drops are fairly round--the small ones spherical, larger ones flattened on the bottom by the airflow. At high speeds, the air resistance increases with the square of the velocity.

By the way, a falling human hurtles to the ground at a terminal velocity of about 125 miles per hour

----

Large raindrops fall at up to 30 feet per second (20 m.p.h.), and an average size raindrop falls about 21 feet per second (14 m.p.h.). When the wind blows, it does affect the drop, it directs it to a angle, not straight down, so the stronger the wind, the more angle the drop will have.

http://www.islandnet.com/~see/weather/history/lenard.htm

A few European scientists briefly looked into the nature of raindrops in the 1800s. The most prominent was Philipp Lenard, a German physicist. He was a brilliant experimental physicist who received the Nobel Prize in physics in 1905 for his work with cathode rays. He studied or taught at many of the major universities in Germany and Eastern Europe during the late nineteenth and early twentieth centuries.

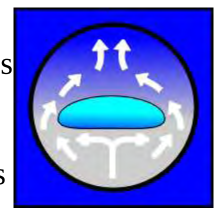
Lenard began studying at raindrops in 1898. At the same time as Lenard began his work on raindrops, investigations of raindrop size were also taking place across the Atlantic on the farm of Wilson A. Bentley, a farmer/scientist best known for his photography of snow crystals. It also appears Lenard was not aware that E.J. Lowe (1892) and J. Wiesner (1895) had made the first measurements of raindrop size a few years previous. Nor was he aware of the work being undertaken by Bentley.

Lenard published the results of his extensive investigation in June 1904 (four months before Bentley would published his findings) in a paper titled *Uber Regen* in the German journal *Meteorologische Zeitschrift*. It presents his work on the shape, size and stability of raindrops during their descent from clouds.

Faced with the problem of how to measure raindrop sizes during a rainstorm, Lenard chose to use blotter paper dusted with a water-soluble dye as a drop collector. When raindrops fell on the impregnated blotter, they produced coloured wet spots which could then be measured. Lenard was concerned that the size of the wet spot on the blotter paper might not reflect the true size of the drop that made it. He thus undertook to establish whether a relationship between the spot size and the drop diameter existed. By dropping known size drops onto the blotter paper and measuring their splash print, Lenard was able to develop a calibration curve for the method.

Lenard partitioned his raindrop data into 0.5 mm (0.02 inch) diameter intervals, reporting it as the number of raindrops of a particular size range falling on an area of one square metre in one second. He used the technique to collect only ten field samples of drop size distribution, and therefore, could not draw many general conclusions relating drop size to rain event conditions. Since Lenard found no drops with diameters less than 0.5 mm (0.02 inch), he did conclude that the updrafts in the clouds must be of sufficient strength to prevent such small drops from falling out. We also know that he only recorded one drop in the 4.75 to 5.25 mm diameter range.

Much of Lenard's work focused on the behaviour of raindrops as they fell from the clouds. To do this, he constructed an innovative vertical wind tunnel in which he could vary the upward speed of the airflow to simulate atmospheric updrafts. And by adjusting the airflow rate, he could briefly balance a drop in the air stream. This balancing act simulated the aerodynamic forces acting on a drop falling freely through a still air column. And a balancing act it was. The turbulence levels in the airflow of his wind tunnel were so high that drops could not be held steady for more than a few seconds.



Using the wind tunnel to observe drop behaviour in an airstream, Lenard could see the actual shape a raindrop took while falling. [A drop's shape is the same whether it is falling through still air or holding its position in an updraft.] By suspending drops of known size, he determined that small drops up to about 2 mm (0.08 inches) in diameter "fell" as spheres. Larger drops, however, deformed while falling acquiring a shape with a flat bottom and rounded top similar to that of a hamburger bun. Thus, Lenard was the first to report that raindrops were not the stereotypical teardrop shape but were spherical when small and shaped much like a hamburger bun when larger.

Drops, however, became unstable at diameters greater than 5.5 mm (0.21 inches), Lenard found. They lasted less than a few seconds before breaking apart in the airflow, torn asunder by the aerodynamic forces acting on the drop. This observation combined with the lack of drops larger than this size in his rainfall measurements led Lenard to conclude that the maximum drop size possible in nature was just larger than 5 mm.

Lenard also used his wind tunnel to determine the fall velocity of drops by increasing the flow rate until the drop became suspended. This flow speed was also the drop's fall velocity. He found that the fall speed increased with drop diameter until a size of 4.5 mm (0.18 inch). For larger drops, however, the fall speed did not increase beyond 8 metres per second (26 ft/sec). He attributed this to the changes in drop shape caused by the air flow as the drop size increased. The change in shape thus increased the air resistance of the drop and slowed its fall rate.

Although Lenard's paper reported many major insights into the shape, size and stability of raindrops, his work, like that of Bentley, was virtually ignored by contemporaries and only years later was he eventually credited for his contribution when other researchers re-discovered his findings. And like Bentley, there was no encore to Lenard's 1904 paper. Neither ever published on this topic again. In part it was due to a lack of interest in the atmospheric sciences in the sub- processes of rain.

But perhaps had Lenard not shifted his interest to other problems in physics, his prestige in the academic world may have forced others to look further into the subject of raindrops. Lenard would only publish one more paper related to atmospheric phenomena in his lifetime. Published in 1915, it dealt with the electrification produced by the splashing and breaking of water drops during free fall

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[PDF]
Simplified Prediction of Driving Rain on Buildings
File Format: PDF/Adobe Acrobat - View as HTML
hourly weather records of **wind speed**, **direction** and rainfall. The value for the Driving Rain
... "Terminal **Fall** Speeds of **Raindrops**", J. of Appl. Meteor., **...**
www.balancedsolutions.com/website/downloads/Eindhoven2000_rain.pdf - Similar pages

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http://www.actsofvolition.com/archives/2004/october/amathphysics

If you are walking from point A to point B in the rain, do you get more or less wet depending on how fast you walk?

Karl Dubost [1:13 AM October 4, 2004]
karl@la-grange.net
http://www.la-grange.net/
Missing factor:

The speed of the rain

You have to consider

d = distance A to B (meters)

t = Time for the person to go from A to B. (seconds)

Speed of the person vp = d/t

Falling Speed of the water is important too.

Imagine one drop of water, only one and imagine you are a flat person. The probability to reach you depends on your speed.
Basically you cant encounter the drop of rain when it's falling from 1 meter to 0.
so vr = 1 / tr .... tr being time in seconds to fall from 1 m to 0.

if you are parcouring your distance in the same time (t) than tr, you will hit the drop of water as a limit, if you do it in less time, you will hit always. If you are longer than one drop of rain to fall. You might avoid it, except if you are not lucky :)

so t > tr to have a chance to not be wet.

tr = 1/vr and t = d/v

so d/v > 1/vr

So your speed to have a probability to not be wet is
d*vr > v

if v is more or equal to vr*d You will be wet for sure.

Hope it helps to solve your problems.

For sure by simplication we take a rain fallin vertically only, the density of the rain doesn't matter much, It's why I have taken one drop of rain.

So basically at a certain point when you run faster, the *probability* of being wet is more important. :)

Probability is the important word here.

chris grzegorczyk [7:23 AM October 4, 2004]
grze@cs.ucsb.edu
http://www.cs.ucsb.edu/
Lets assume that a rain drop is a point, in the mathematical sense, i.e. it is dimensionless. This means that for some raindrop, call it r, the statement r (belongs to) U, where U denotes the set of points in R^3 which are contained in the closed set defined

by your cube. Further, lets assign the rain the falling properties:
Rain falls in sheets of dimensions 1xinfinity, that is, they are 1 unit in width, and infinitely tall.
These sheets of rain contain k rain drops per 1x1. And more so, the entire path of travel contains k^2 rain drops in any 1x1x1 space.
Finally, all rain drops travel @ v units/s with a phase which is normal to the surface of the path. i.e. they fall straight down.

Consider this point of view: The rain is stationary, but you are walking up a slope whose angle is a function of your velocity. So if you were to move with an infinite speed in the original scenario, the rain would not manage to fall at all, and all the rain you come into contact with would be on the front of your cube. Under this new point of view, the slope of your path would be 0. If you had 0 velocity, the slope of your line would be infinite. What we are actually talking about is your position function, which will be linear and depend upon the specific distances involved. So now we can find the amount of rain you come into contact with.

A little geometric observation leads to the realization that the volume occupied by rain through which you travel will be a parallelogram, one for your front, and one for your top. Lets say that we know the function modelling your position, call it f(t), then f(t_0)=0, and f(t_n)=L (where t_n is your final time, and L the length of the path). Then the volume of rain you pass through is given by the sum of the rain on your head and the rain on your front:

Let d_t denote the surface area of your top, and d_f denote the surface area of your front, and L is the length of the path, and t_n be the length of the path divided by your velocity (assumed to be constant). Denote the position function as f(t), then f(t_0)=0, and f(t_n)=L, which will be linear. Let R be the rain function,
R = sqr(L^2 + t_n^2) * [(d_t * sin(arctan(L / t_n)))
+ (d_f * sin(pi/2 - arctan(L / t_n)))]

Note that L, d_t, and d_f are all predetermined, so only t_n is variable, and depends on your velocity. At this point an approach can be made at minimizing R by taking the derivative and looking for roots. enjoy...

-c

god forbid i make an arbitrary guess here, but according to this setup, the faster you go, the dryer you stay. It follows simply from the observation that R is minimized as t_n approaches 0, where the limit for R is d_f*(L*t_n).

Dan [6:14 AM October 4, 2004]
well assuming that everythig is evenly distributed and rectangles you can take the prblem into 2 parts. First if the rain hitting the top of you. The answer for this is the amount of water for your given area per second times the seconds you are in the rain. The walker loses here. Second for the rain hitting you from your direction of travel the equation can be made in much the same way. Take the average amount of water for your given area and multiply by distance traveled. For this both come out equal. Add the two results togeather and the runner wins as fewer drops of rain hit the head of the runner. This of course assumes perfect water absorbtion no wind and an evenly distributed rain. QED

shell [11:24 PM October 4, 2004]
shell_at@at_slact_dot.dot_net
Assuming the position of rain particles is random enough, we can arrive at a spread rate, or areal density, for rain. Let's call that R_s. Let L, W, and H be the Length, Width, and Height of the man-rectangle.
We are then interested in the incidence area the man-box makes with the rain.
Treating rain from the frame of reference of the man-box, we get

$$Wetness = W\ R_s\ t\ A$$

where A is the incidence area.

Since we are dealing with a simple man-box, no integration is needed, so

$$Wetness = W \cdot R_s \cdot t \frac{L \cdot V_{rain} + H \cdot V_{run}}{\sqrt{{V_{rain}}^2 + {V_{run}}^2}}$$

Remembering that we are covering a given distance,

$$Wetness = W \cdot R_s \frac{d}{V_{run}} \frac{L \cdot V_{rain} + H \cdot V_{run}}{\sqrt{{V_{rain}}^2 + {V_{run}}^2}}$$

Stephen A. Meigs [5:56 PM October 11, 2004]
step314@aol.com
http://members.aol.com/step314/index.htm

If there's a tailwind that is sufficiently strong, you are best off walking (or running?) at the exact speed of the tailwind. That way, your front (and back) won't get wet at all. The condition for when you should move at tailwind speed is v_f > ((A_t)(v_d) + (A_s)(v_s))/A_f, where

v_f is the forward component of the rain velocity
A_t is the top area
v_d is the downward component of the rain velocity
A_s is the lateral (side) area
v_s is the lateral (side) component of the rain velocity
A_f is the frontal area

Here, v_w and v_s are to be calculated with respect to a
reference frame fixed relative to the ground (with axes pointing in the obvious directions).

If the inequality is not satisfied, run as fast as possible.

Jesse [1:40 PM October 12, 2004]
http://www.jinfoong.net/jesse
The rain has a flux F (drops/m^2/s)
The box has dimensions L x W x H
The distance to travel is D
The box velocity is vb
The rain velocity is vr

If you imagine the box sitting still for 1 second, the # drops N would be N = F*L*W
But if the box is moving it will not only capture all the drops hitting its top, but also all the drops that are moving in front of it. This effectively increases the box's length by the ratio between the box speed and the drop speed times the height L' = L + H*vb/vr.

So the total drops N would be

N = F*L'*W* (D/vb) = F*W*D*(L/vb + H/vr)

So if you're going a fixed distance, it's always better to run. If you're going for a fixed time, it's better to stay still. Relativistic effects are ignored for simplicity.

nobody special [12:36 AM January 22, 2005]
Here's what I get (after some kindergarten level geometry) : the inclined walk visualization of chris works just fine for this.

If the dimensions of the man are H (tall), W (wide) and T (thick), the terminal velocity of the raindrops is v1, the man's speed is v2, and the density of drops per unit volume is n, then the number of drops hitting the man over a time t is :

N = nV = nWA = nW[(H + tv1)(T + tv2) - (t^2)v1v2 - HT] = nWt(Hv1 + Tv2)

If the time in the rain, t, is fixed, then N = Cv2, so, it's better to stay still.

If the distance d, is fixed, then t = d/v2, and hence :

N = nWd[H + T(v1/v2)], so this is minimized by maximizing v2. Hence, the faster you run, the drier you stay.

BArry

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http://72.14.253.104/search?q=cache:2YZ9-fqmD_UJ:www.wmo.ch/web/www/IMOP/publications/CIMO-Guide/Draft%25207th%2520edition/Part1-Ch13Final_Corr.pdf+Can+the+speed+and+direction+of+wind+be+determined+from+the+slant+angle+that+rain+drops+make+while+falling%3F&hl=en&ct=clnk&cd=8&gl=us

CHAPTER 13 – MEASUREMENT OF UPPER **WIND**
I.13œ1

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, 2003):
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 **U**SES 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 **I**MPROVEMENTS 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** 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-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 in
this Part. 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 **A**
CCURACY REQUIREMENTS
Accuracy requirements for upper-**wind** measurements are presented in terms of **wind** **speed** and **direction** in Annex 12.A,
Chapter 12 in this Part. A summary of performance limits for upper-**wind** measurements in terms of standard vector errors is
found in Table 1, Annex 12.B, Chapter 12 in this Part. 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 Table 1, Annex 12.B,
Chapter 12 in this Part. 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 Table 1, Annex 12.B, Chapter 12 in this Part is 300 to
400 m in the troposphere and 600œ800 m in the stratosphere. A higher vertical resolution (50œ150 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 Annex 12.A, Chapter 12 in this Part, 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 minutes 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

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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 Annex 12.A, Chapter 12 in this Part 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 method will be considered
here.

13.1.4.1 **T**
RACKING 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 (see section 13.2.4) to track a
reflecting target carried by the balloon, a radiotheodolite or secondary radar (see section 13.2.4.2) 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.

Modern Rradiotheodolite systems with antenna dimensions less than 2 m are best suited for upperwind measurements when balloon elevations stay above 10œ15°. 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 radio frequency spectrum in the —Meteorological-Aids bands“ to be practical in many countries.

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

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 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.

13.1.4.2 **T**
RACKING 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 Loran, is described in WMO (1985). Radiosonde manufacturers have

been offering radiosondes with a satellite-based global positioning system (GPS) since 1995 (WMO, 1994 and Kaisti, 1995).

Reliable operations took some time to achieve, but most of the major problems were resolved by the time of the WMO GPS
Radiosonde Comparison in Brazil (WMO, 2002). Height measurements with code correlating GPS systems are now
sufficiently accurate to replace pressure sensors in modern radiosondes.
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.
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 Loran navaid systems. The static on the
radiosonde aerial will normally discharge later in the flight when satisfactory measurements will again become possible. GPS
radiosonde systems do not suffer from this problem.

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 in this Part **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 in this Part 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 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 multi-path interference and is usually the limiting factor in radiotheodolite tracking capability at low elevations. The amount of multipart 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 multi-path interference problems at elevations as high as 16°. When multi-path 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 **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 upwind 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 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 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 in this Part **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 determine 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 radio frequency 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 **R**
ADAR 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 performance 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 a 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 **T**RANSPONDER 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 Loran systems using
ground-based transmitters and the satellite-based GPS.
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 radio frequency 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. GPS **wind** measurements are of better accuracy than **wind** measurements by most
other operational systems.
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 **A**
VAILABILITY OF NAVAID SIGNALS IN THE FUTURE

A major change in the availability of navaid signals has occurred. The VLF Omega system has been decommissioned.
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 radio-frequency than 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. The resultant GPS **wind** measurement accuracy is better than good primary radars.

13.2.5.2 VERY LOW FREQUENCY (VLF) NETWORKS

The Russian Alpha navigation network operates at VLF. There are also a limited number of additional regular VLF transmissions of sufficient stability that **can** also be exploited for **wind** measurements. 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.

At the chosen frequencies (wavelengths 22 to 30 km) the ionosphere and Earth‘s surface act as a waveguide. The VLF 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 VLF signals received by the radiosonde aerial are used to modulate the radiosonde carrier frequency. The VLF signals are then stripped from the carrier after reception by the radiosonde receiver and fed to the tracker in the ground system. The rates of change of phase of the VLF 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 Loran-C chains are being modernized and automated.
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
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.
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 **G**
LOBAL POSITIONING SYSTEM
(GPS)

The 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 ‡ 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 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 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 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 Loran, or as a digital data stream). The pre-processing **can** be achieved by a variety of

techniques. 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 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 radiosondes were quite susceptible to external radio frequency interference, since the radiosonde navaid
receiver sensitivity was designed to be adequate for the weak GPS signal strengths. In more recent designs, protection against
external radio frequency interference has been optimized in the radiosonde design.
GPS radiosondes are now used in more than a quarter of the global radiosonde network. The majority of the systems in
use from 2005 onwards will identify the GPS signals by decoding the C/A code. These radiosondes will then be able to
provide accurate positions in three dimensions throughout the radiosonde ascent.
The main practical consideration with GPS radiosondes is the time taken for the GPS tracker on the radiosonde to
synchronize to the signals being received from the satellite. It is unwise to launch the radiosonde until this synchonization has
been achieved. This may require the radiosonde to be placed outside for several minutes before launch or alternatively a
method arranged to transmit GPS signals to the radiosonde where it is being prepared.

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 artifacts 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 non-linear 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 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.

At heights up to about 24 km, the comparison of radar height measurements with 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 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 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 radionavigational systems

In order to derive satisfactory upper-**wind** measurements from ground-based radionavigation systems, 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).
The geometry for using satellite navigation signals is such that GPS **wind** finding algorithms seem to work most reliably
when signals are received from at least eight satellites during the ascent. The GPS almanac **can** be used to identify times
when satellite geometry is weak for windfinding. In practice, this does not occur very often with the current satellite
configuration.
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.
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 **T**
ARGET 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 **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, 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.
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 **T**
ARGET 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:

ε_v^2

= 2 · [ε

$$\ldots_r^2 \cdot Q^2/(Q^2 + 1) + \varepsilon_\theta^2 \cdot h^2 + \varepsilon_\varphi^2 \cdot h^2 \cdot Q^2]/t^2 \qquad (13.1)$$

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

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

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 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 13.1 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 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.

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
ν
at
5 km
ε
ν
at
10 km
ε
ν
at
15 km
ε
ν
at
20 km
ε
ν
at
25 km
ε
ν
at
30 km
ε
ν
at
5 km
ε
ν
at
10 km
ε
ν
at
15 km
ε
ν
at
20 km
ε
ν
at
25 km
ε
ν
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
2.5
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
(α
εv
= tangential error/radial error)

Radar
Radiotheodolite
Q
α
εv
,
5 km
α
εv
,
10 km
α
εv
15 km
α
εv
,
20 km
α
εv
,
25 km
α
εv
,
30 km
α
εv
,
5 km
α
εv

,
10 km
α
εν
,
15 km
α
εν
,
20 km
α
εν
,
25 km
α
εν
,
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
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 jet streams. The smaller portable radiotheodolite deployed by United States in Japan had the largest wind errors at high *Q* because of problems with multi-path 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. 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 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 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 the signal strength. The fluctuations in signal strength and stability can be so large that, in some locations, successful wind measurement with 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.

13.5.4.1 **L**
ORAN
-C
WINDFINDING SYSTEMS

Commercially available systems produce wind data of good quality as indicated in Table 13.5. 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 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 recent WMO tests of GPS
radiosondes. The main difference between systems comes from the filtering applied to the winds to remove the pendulum
motion of the radiosonde. GPS wind measurements are at least as reliable as the very 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 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.

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})
Loran-C
[ground wave]
30œ60
up to ±0.2
0.6œ3
Loran-C
[sky wave]
60œ120
up to ±0.2
1.6œ4
GPS
5
up to ±0.1
0.2- 0. 6*

* Value taken from Elms and Nash, 1996.

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 **O**
PERATIONAL 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 six per cent of the upperwind 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 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 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, though antenna systems, cables and connectors should be regularly inspected for corrosion and other weathering effects. 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.

TABLE 13.6

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

Plan range *(km)*	*Altitude* *(km)*	Δz *curvature*	Δz *refraction 60N 01W*	Δz *refraction 36N 14E*	Δz *refraction 1S 73E*
25	10	49	-9	-10	-12
50	15	196	-31	-34	-39
100	20	783	-106	-117	-133
150	25	1760	-211	-231	-262
200	30	3126	-334	-363	-427

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