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# CHAPTER 15. OBSERVATION AND MEASUREMENT OF CLOUDS

## 15.1 GENERAL

The observation or measurement of clouds and the height of their bases above the Earth's surface are important for many purposes, especially for aviation and other operational applications of meteorology. An important application for the observation or measurement of cloudiness during daytime is the solar power forecasting for photovoltaic systems. This chapter describes the methods in widespread use. Important further information is to be found in WMO (2017), which contains scientific descriptions of clouds and illustrations to aid in the identification of cloud types. Information on the practices specific to aeronautical meteorology is given in WMO (2014).

### 15.1.1 Definitions

*Cloud*: An aggregate of very small water droplets, ice crystals, or a mixture of both, with its base above the Earth's surface, which is perceivable from the observation location. The limiting liquid particle diameter is of the order of 200 $\mu$m; drops larger than this comprise drizzle or rain.

With the exception of certain rare types (for example, nacreous and noctilucent) and the occasional occurrence of cirrus in the lower stratosphere, clouds are confined to the troposphere. They are formed mainly as the result of condensation of water vapour on condensation nuclei in the atmosphere. Cloud formation takes place in the vertical motion of air, in convection, in forced ascent over high ground, or in the large-scale vertical motion associated with depressions and fronts. Clouds may result, in suitable lapse-rate and moisture conditions, from low-level turbulence and from other minor causes. Human activity, such as aviation or industry, can also result in cloud formation, by adding condensation nuclei to the atmosphere.

At temperatures below 0 °C, cloud particles frequently consist entirely of water droplets supercooled down to about –10 °C in the case of layer clouds and to about –25 °C in the case of convective clouds. At temperatures below these very approximate limits and above about –40 °C, many clouds are "mixed", with ice crystals predominating in the lower part of the temperature range.

*Cloud amount*: The amount of sky estimated to be covered by a specified cloud type (partial cloud amount), or by all cloud types (total cloud amount). In either case, the estimate is made to the nearest okta (eighth) and is reported on a scale which is essentially one of the nearest eighth, except that figures 0 and 8 on the scale signify a completely clear and cloudy sky, respectively, with consequent adjustment to the adjacent 1 and 7 okta intervals (see 15.1.4.1).

*Cloud base*: The lowest zone in which the obscuration corresponding to a change from clear air or haze to water droplets or ice crystals causes significant changes in the profiles of the backscatter and extinction coefficients. In the air below the cloud, the particles causing obscuration show some spectral selectivity, while in the cloud itself, there is virtually no selectivity; the difference is due to the different droplet sizes involved. The height of the cloud base is defined as the height above ground level. For an aeronautical meteorological station, the ground (surface) level is defined as the official aerodrome elevation.

*Cloud type* (classification): Various methods of cloud classification are used, as follows:

(a) In WMO (2017), division is made into cloud genera with 10 basic characteristic forms, with further subdivision, as required, into:

   (i) Cloud species (cloud shape and structure);

   (ii) Cloud varieties (cloud arrangement and transparency);

   (iii) Supplementary features and accessory clouds (for example, incus, mamma, virga, praecipitatio, arcus, tuba, pileus, velum and pannus);

   (iv) Growth of a new cloud genus from a mother-cloud, indicated by the addition of "genitus" to the new cloud and mother-cloud genera – in that order, if a minor part of the mother-cloud is affected – and of "mutatus" if much or all of the mother-cloud is affected, for example, stratocumulus cumulogenitus, or stratus stratocumulomutatus;

   (v) Special clouds that form or grow as a consequence of certain, often localized, generating factors. These may be either natural, or the result of human activity (for example, flammagenitus, cataractagenitus and aircraft condensation trails);

(b) A classification is made in terms of the level – high, middle or low – at which the various cloud genera are usually encountered. In temperate regions, the approximate limits are: high, 6–12 km (20 000–40 000 ft); middle, surface–6 km (0–20 000 ft); and low, surface–1.5 km (0–5 000 ft). The high clouds are cirrus, cirrocumulus and cirrostratus; the middle clouds are altocumulus and altostratus (the latter often extending higher) and nimbostratus (usually extending both higher and lower); and the low clouds are stratocumulus, stratus, cumulus and cumulonimbus (the last two often also reaching middle and high levels);

   For synoptic purposes, a nine-fold cloud classification is made in each of these three latter divisions of cloud genera, the corresponding codes being designated $C_H$, $C_M$ and $C_L$, respectively. The purpose is to report characteristic states of the sky rather than individual cloud types;

(c) Less formal classifications are made as follows:

   (i) In terms of the physical processes of cloud formation, notably into heap clouds and layer clouds (or "sheet clouds");

   (ii) In terms of cloud composition, namely ice-crystal clouds, water-droplet clouds and mixed clouds.

Most of these forms of cloud are illustrated with photographs in WMO (2017).

*Vertical visibility*: The maximum distance at which an observer can see and identify an object on the same vertical as him/herself, above or below. Vertical visibility can be calculated from the measured extinction profile, $\sigma(h)$. The relationship, however, is less simple than for horizontal visibility, because $\sigma$ may not be regarded as a constant value. Nevertheless, the $I(h = VV)/I_0 = 5\ \%$ rule can be applied. Taking into account this assumption, the vertical visibility can be expressed in a relation with $\sigma(h)$, in which $VV$ is represented intrinsically, i.e.:

$$\int_{h=0}^{h=VV} \sigma(h)\,dh = -\ln(5\%) \approx 3 \qquad (15.1)$$

See also Volume III, Chapter 2, equations 2.6 and 2.7.

### 15.1.2 Units and scales

The unit of measurement of cloud height is the metre or, for some aeronautical applications, the foot. The unit of cloud amount is the okta, which is an eighth of the sky dome covered by cloud.

In BUFR FM 94 code (WMO, 2011) total cloud cover is given in percentage (113 indicating sky obscured by fog and/or other meteorological phenomena).

### 15.1.3 Meteorological requirements

For meteorological purposes, observations are required for cloud amount, cloud type and height of cloud base. For synoptic observations, specific coding requirements are stated in WMO (2011), which is designed to give an optimum description of the cloud conditions from the surface to high levels. From space, observations are made of cloud amount and temperature (from which the height of the cloud top is inferred). Measurements from space can also be used to follow cloud and weather development.

Uncertainty requirements are stated in Volume I, Chapter 1, Annex 1.A.

### 15.1.4 Observation and measurement methods

#### *15.1.4.1 Cloud amount*

Traditionally, measurements of cloud amount were made by visual observation. Instrumental methods are now widely accepted and are used operationally in many applications for determination of cloud amount and height. The cloud amount in each identified layer and the total cloud amount in view of the observation point are determined.

The total cloud amount, or total cloud cover, is the fraction of the celestial dome covered by all clouds visible. The assessment of the total amount of cloud, therefore, consists in estimating how much of the total apparent area of the sky is covered with clouds.

The partial cloud amount is the amount of sky covered by each type or layer of clouds as if it were the only cloud type in the sky. The sum of the partial cloud amounts may exceed both the total cloud amount and eight oktas.

The scale for recording the amount of cloud is that given in Code table 2700 in WMO (2011), which is reproduced below:

TABLE: Table as text NO space

| Code figure | Meaning | |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 1 okta or less, but not zero | 1/10 or less, but not zero |
| 2 | 2 oktas | 2/10–3/10 |
| 3 | 3 oktas | 4/10 |
| 4 | 4 oktas | 5/10 |
| 5 | 5 oktas | 6/10 |
| 6 | 6 oktas | 7/10–8/10 |
| 7 | 7 oktas or more, but not 8 oktas | 9/10 or more, but not 10/10 |
| 8 | 8 oktas | 10/10 |
| 9 | Sky obscured by fog and/or other meteorological phenomena | |
| / | Cloud cover is indiscernible for reasons other than fog or other meteorological phenomena, or observation is not made | |

#### *15.1.4.2 Cloud-base height*

The height of the cloud base lends itself to instrumental measurement, which is now widely used at places where cloud height is operationally important. However, the estimation of cloud-base height by human observer is still widespread.

Several types of instruments are in routine operational use, as described in this chapter. An international comparison of several types of instruments was conducted by WMO in 1986, and is reported in WMO (1988). The report contains a useful account of the accuracy of the measurements and the performance of the instruments.

Recent studies (WMO, 2016a and 2016b) showed the enhanced performance of modern ceilometers concerning the detection of the cloud-base height of very low clouds, very high clouds and during precipitation. However the studies revealed systematic differences in the cloud-base heights reported by ceilometers from different manufacturers of 30–50 metres. As the shapes of the profiles and the location of the gradients and maxima in the measured backscatter are quite similar, the cloud detection algorithms implemented by the manufacturers appear to be the source of these differences. The algorithm may place the cloud base at the altitude where the backscatter starts to increase significantly or higher up allowing for a penetration depth into the cloud or at the maximum of the backscattered signal. The different approaches cannot be verified at this time because the lack of an established and quantifiable definition for cloud base, and the lack of a suitable reference. Comparison of ceilometer cloud-base heights with visibility measurements at various altitudes up a mast, and the height up a tower that can be discerned from a camera image, are both currently under investigation to ensure the correct operation of a ceilometer.

Instrumental measurement of cloud-base height is common and important for aeronautical meteorological services. This is discussed further in Volume III, Chapter 2.

#### *15.1.4.3 Cloud type*

At present, the only method for observing most cloud types is visual. Pictorial guides and coding information are available from many sources, such as WMO (2011, 2017), as well as from publications of National Meteorological Services.

The extraction of cloud type from camera images is still under development (see for example Heinle et al., 2010 and Liu et al., 2011).

Some meteorological offices use lightning, weather radar and satellite information to identify Cumulonimbus (CB) and Towering Cumulus (TCU) for inclusion in automated aeronautical weather reports when appropriate.

## 15.2 ESTIMATION AND OBSERVATION OF CLOUD AMOUNT, CLOUD-BASE HEIGHT AND CLOUD TYPE BY HUMAN OBSERVER

### 15.2.1 Making effective estimations

The site used when estimating cloud variables should be one which commands the widest possible view of the sky, and it should not be affected by fixed lighting which would interfere with observations at night. In making observations at night, it is very important that the observer should allow sufficient time for the eyes to adjust to the darkness.

There are, of course, occasions when it is very difficult to estimate cloud amount, especially at night. The previous observation of cloud development and general knowledge of cloud structure will help the observer to achieve the best possible result. Access to reports from aircraft, if available, can also be of assistance.

### 15.2.2 Estimation of cloud amount

The observer should give equal emphasis to the areas overhead and those at the lower angular elevations. On occasions when the clouds are very irregularly distributed, it is useful to consider the sky in separate quadrants divided by diameters at right angles to each other. The sum of the estimates for each quadrant is then taken as the total for the whole sky.

Code figure 9 is reported when the sky is invisible owing to fog, falling snow, etc. or when the observer cannot estimate cloud amount owing to darkness or extraneous lighting. During moonless nights, it should usually be possible to estimate the total amount by reference to the proportion of the sky in which the stars are dimmed or completely hidden by clouds, although haze alone may blot out stars near the horizon.

The observer must also estimate the partial cloud amount. There are times, for example, when a higher layer of cloud is partially obscured by lower clouds. In these cases, an estimate of the extent of the upper cloud can be made with comparative assurance in daylight by watching the sky for a short time. Movement of the lower cloud relative to the higher cloud should reveal whether the higher layer is completely covering the sky or has breaks in it.

It should be noted that the estimation of the amount of each different type of cloud is made independently of the estimate of total cloud amount. The sum of separate estimates of partial cloud amounts often exceeds both the total cloud amount, as well as eight oktas.

### 15.2.3 Estimation of cloud-base height

At stations not provided with measuring equipment, the values of cloud-base height can only be estimated. In mountainous areas, the height of any cloud base which is lower than the tops of the hills of the mountains around the station can be estimated by comparison with the heights of well-marked topographical features as given in a contour map of the district. It is useful to have, for permanent display, a diagram detailing the heights and bearings of hills and the landmarks which might be useful in estimating cloud height. Owing to perspective, the cloud may appear to be resting on distant hills, and the observer must not necessarily assume that this reflects the height of the cloud over the observation site. In all circumstances, the observer must use good judgment, taking into consideration the form and general appearance of the cloud.

The range of cloud-base heights above ground level which are applicable to various genera of clouds in temperate regions is given in the table below and refers to a station level of not more than 150 m (500 ft) above mean sea level. For observing sites at substantially greater heights, or for stations on mountains, the height of the base of the low cloud above the stations will often be less than indicated in the table below.

In other climatic zones, and especially under dry tropical conditions, cloud-base heights may depart substantially from the given ranges. The differences may introduce problems of cloud classification and increase the difficulty of estimating the height. For instance, when reports on tropical cumulus clouds of an obviously convective origin, with a base well above 2 400 m (8 000 ft) or even as high as 3 600 m (12 000 ft), have been confirmed by aircraft observations. It is noteworthy that, in such cases, surface observers frequently underestimate cloud heights to a very serious degree. These low estimates may be due to two factors, namely either the observer expects the cumulus cloud to be a “low cloud” with its base below 2 000 m (6 500 ft) and usually below 1 500 m (5 000 ft), or the atmospheric conditions and the form of the cloud combine to produce an optical illusion.

When a direct estimate of cloud-base height is made at night, success depends greatly on the correct identification of the form of the cloud. General meteorological knowledge and close observation of the weather are very important in judging whether a cloud base has remained substantially unchanged or has risen or fallen. A most difficult case, calling for great care and skill, occurs when a sheet of altostratus covers the sky during the evening. Any gradual lowering of such a cloud sheet may be very difficult to detect, but, as it descends, the base is rarely quite uniform and small contrasts can often be discerned on all but the darkest nights.

**Cloud-base height genera above ground level in temperate regions**

**TABLE: Table horizontal lines**

| *Cloud genera* | *Usual range of height of base*[a] | | *Wider range of height of base sometimes observed, and other remarks* | |
|---|---|---|---|---|
| | *(m)* | *(ft)* | *(m)* | *(ft)* |
| **Low** | | | | |
| Stratus | Surface–600 | Surface–2 000 | Surface–1 200 | Surface–4 000 |
| Stratocumulus | 300–1 350 | 1 000–4 500 | 300–2 000 | 1 000–6 500 |

| | | | | |
|---|---|---|---|---|
| Cumulus | 300–1 500 | 1 000–5 000 | 300–2 000 | 1 000–6 500 |
| Cumulonimbus | 600–1 500 | 2 000–5 000 | 300–2 000 | 1 000–6 500 |
| **Middle** | (km) | | | |
| Nimbostratus } | Surface–3 | Surface–10 000 | Nimbostratus is considered a middle cloud for synoptic purposes, although it can extend to other levels | |
| Altostratus | 2–6 | 6 500–20 000 | Altostratus may thicken with progressive lowering of the base to become nimbostratus | |
| Altocumulus | | | | |
| **High** | | | | |
| Cirrus } | | | Cirrus from dissipating cumulonimbus may occur well below 6 km (20 000 ft) in winter | |
| Cirrostratus | 6–12 | 20 000–40 000 | Cirrostratus may develop into altostratus | |
| Cirrocumulus | | | | |

Note:
a For stations over 150 m above sea level, the base of low-level clouds will often be less than indicated.

### 15.2.4 Observation of cloud type

Observation of cloud type is still widely performed by human observers. Pictorial guides and coding information are available from many sources, such as WMO (2017), as well as from publications of National Meteorological Services.

## 15.3 INSTRUMENTAL MEASUREMENT OF CLOUD AMOUNT

Multiple types of ground-based operational sensors are available to measure total cloud amount. Measurements from space-borne radiometers in the visible band, supplemented by infrared images, can be used to estimate cloud amounts over wide areas, even though difficulties are often experienced, for example, the inability to distinguish between low stratus and fog. Amounts of cloud within the range of a ceilometer can be estimated by measuring the proportion of elapsed time occupied by well-identified layers and assuming that these time-averaged results are representative of the spatial conditions around the observing site. This technique gives generally satisfactory results but it can lead to significant differences with the visually estimated cloud amount due to the limited spatial representativeness of the sky sampled by the ceilometer. For automatic weather stations in the United States, a "clustering" technique has been developed using data from ceilometers. Other countries, like Sweden (Larsson and Esbjörn, 1995) and the Netherlands (Wauben, 2002), have introduced similar techniques in their operational observations. Automated cloud measurements using ceilometers are also used at airports by several meteorological offices. This technique has been used to obtain cloud information at small airports without an observer, and also at bigger airports where the automated system provides a cost effective method of information collection.

Other instruments used to measure cloud amount are pyrometers which may sample in multiple fixed directions and/or scan the sky, and sky cameras that are designed specifically for this purpose. By suitable processing such information can also be derived from commercial camera systems, and visible and infrared webcams.

### 15.3.1 Laser ceilometer measurement of cloud amount

Several meteorological services use time series of cloud base measurements from laser ceilometers (see 15.4.1) to determine cloud amount. This method has some advantages compared to manual observations. Using a ceilometer gives more consistent results. Also, output can be generated more frequently and there are no problems during night-time. However, there are also some drawbacks and large deviations can occur in situations with high, thin cirrus clouds when the performance of the ceilometer is reduced; when a moist layer is reported as a cloud base by the ceilometer; when a ceilometer detects no cloud base or at the wrong height during precipitation; and when the ceilometer reports a cloud base at the lowest elevation during shallow fog. This method also relies on the clouds to move over the field of view of the instrument. Clouds do not always move in that way. Even if clouds do move across the field of view of the ceilometer, these clouds may not be representative of the total sky. Thus, the time series of the cloud base may not always represent the total sky, on which the reporting of cloud cover should be based.

Most differences can be attributed to the limited spatial representativeness of a ceilometer sampling only a small area directly overhead. Agreements (within 2 okta) between this method and manual observation of total cloud amounts are typically 85 %–90 %, as found for coastal stations at mid-latitudes (WMO, 2006*a*). These results are affected by the relatively large number of overcast situations (7 or 8 okta occurs about 55 % of the time). A characteristic difference between the ceilometer and observed total cloud amount is that the ceilometer with the limited view of the sky will report 8 okta much more often than 7 okta, whereas an observer can detect gaps anywhere in the cloud cover resulting in nearly equal occurrences of 7 and 8 okta.

Some airports are equipped with several ceilometers and a multiple-ceilometer sky condition algorithm. However, evaluation at an airport has shown only small improvements when using three ceilometers compared to one (Wauben, 2002). This indicates that monitoring three points instead of one is still not sufficient to get a representative value for the entire sky.

As an example of cloud amount measurement with laser ceilometers, the United States National Weather Service’s Automated Surface Observing System (ASOS) method is described in the following.

The cloud height indicator (laser ceilometer – see 15.4.1) compiles samples of backscatter return signals every 30 s and determines the height of valid cloud “hits”. Every minute, the last 30 min of 30 s data are processed to give double weighting to the last 10 min in order to be more responsive to recent changes in sky condition. The data are then sorted into height “bins”.

Each minute, if more than five height bin values have been recorded (during the last 30 min), the cloud heights are clustered into layers using a least-square statistical procedure until there are only five bins remaining (each bin may have many hits in it). These bins, or clusters, are then ordered from lowest to highest height. Following this clustering, the ASOS determines whether clusters can be combined and rounded, depending on height, into meteorologically significant height groups. The resulting bins now are called “layers” and the algorithm selects up to three of these layers to be reported in the METAR/SPECI in accordance with the national cloud layer reporting priority.

The amount of sky cover is determined by adding the total number of hits in each layer and computing the ratio of those hits to the total possible. If there is more than one layer, the hits in the first layer are added to the second (and third) to obtain overall coverage. For reporting purposes, the ASOS-measured cloud amount for each layer is then converted to a statistical function equivalent to a human observation.

The algorithm also tests for total sky obscuration based on criteria of low surface visibility and a high percentage of “unknown hits” at low levels.

A sky condition algorithm has also been developed for use where cloud formation (or advection) typically occurs in (or from) a known location and results in significant concurrent differences in sky conditions over an airport. This meteorological discontinuity algorithm uses input from two cloud-height indicator sensors. The primary sensor is sited near the touchdown zone of the primary instrument runway. The second sensor is typically sited 3 to 6 km (2 to 4 miles) from the primary sensor, upwind in the most likely direction of the advection, or closer to the fixed source of the unique sky condition. The second cloud-height indicator serves to detect operationally significant differences in sky conditions.

Further details on the ASOS sky condition algorithm and its verification are provided by NOAA (1988) and the United States Government (1999).

### 15.3.2 Infrared detector measurement of cloud amount

Pyrometers, or passive infrared radiometers, are basically remote-sensing infrared thermometers (8–14 $\mu$m). These can be used to observe elementary solid angles of the sky either by using multiple fixed sensors (for example, four fixed sensors used to sample the whole sky), by scanning the entire sky dome with a single sensor, or by a combination of the two methods (one manufacturer’s design has 14 sensors across 180 degrees of elevation from one horizon to the opposite horizon, and a physical mechanism scans the azimuth). The downward thermal emission from the clouds and from the air column between clouds and the instrument is measured and the temperature of each sampled solid angle is derived from a combination of the Planck and the Stefan-Boltzmann laws. The infrared temperature can then be used to provide an indication of cloud presence in each sampled solid angle. The total proportion of sky containing cloud can then be derived and reported as the cloud cover.

Scanning pyrometers avoid the problems of representativeness of the measurement that is present in other methods, depending on the number of points sampled. Also, nocturnal observations are possible. A disadvantage is that fractioned and/or transparent "pixels" are difficult to classify. For example a scanning pyrometer, the so-called NubiScope, can be operated continuously for routine measurements of the total cloud amount (WMO, 2010). Every 10 minutes a scan of the sky is obtained with a resolution of 36 by 30 pixels. The pyrometer is located at the end of the tube making it quite insensitive to contamination. The cloud detection threshold is about -65 °C, but depends on the contamination of the lens, the contribution of water vapour to the measured brightness temperature and the optical depth of the cloud. The NubiScope detects clouds when the measured atmospheric brightness temperature is above the clear sky background value. The clear sky brightness temperature increases with larger zenith angles, due to the increasing slant path through the atmosphere, and varies over time due the variations in atmospheric water vapour. The sensor adapts the clear sky reference dynamically during each scan when sufficient cloud free scenes at various elevations are available. Boers et al. (2010) concluded that a hemispheric cloud observation method (such as the NubiScope) instead of a column method (such as a ceilometer) should be used to replace an observer in order to avoid discontinuities in the cloudiness distribution function of climate records.

Infrared sky camera systems using uncooled micro-bolometer detector arrays measure the downwelling atmospheric radiation in the 8-14 µm wavelength band. The so-called Whole-Sky InfraRed Cloud Measuring System (Liu et al., 2013) combines several infrared images of the sky to get a whole sky image every 15 minutes with a resolution of 650 by 650 pixels. The processing of the infrared images for cloudiness is similar to that of a scanning pyrometer. The system uses real-time temperature and relative humidity profiles and horizontal visibility data to optimize the threshold for cloud base detection. In addition, the high spatial resolution allows derivation of the cloud type as for a visual camera.

Pyrgeometers measure the downward atmospheric long wave radiation (4.5-100 µm). The level of long wave radiation and its variability can be used to estimate the total cloud amount (Dürr and Philipona, 2004).

### 15.3.3 Sky camera measurement of cloud amount

Cameras specifically designed to measure cloud amount exist. They view the total sky using, for example, curved mirrors. The image from the sky is analysed by an algorithm that determines whether a cloud is present in each pixel using the measured colour. The sum of all pixels results in cloud amount. In the past specifically designed sky imagers were used during daytime only to estimate the total cloud amount. Nowadays DSP (Digital Signal Processing) IP cameras or webcams can be used for that purpose, whereas cameras with infrared night vision also give useful results in low lighting conditions. Extensive developments have been achieved in the software that is used to analyse sky images in order to determine not only cloud amount but also cloud type (see for example, Wacker et al., 2015).

This method avoids the problems of representativeness of the measurement that can be present in some other methods. Some cameras use daylight and are thus not applicable at night. Cameras measuring in the infrared do not have this disadvantage, but these have a smaller field-of-view and are more expensive. Sky cameras require frequent maintenance in the form of cleaning of the optical surfaces.

## 15.4 INSTRUMENTAL MEASUREMENT OF CLOUD-BASE HEIGHT

Several methods exist for measuring cloud-base height. They are: using a laser ceilometer, using a rotating beam ceilometer, using a searchlight and using a balloon. The method currently most used is the laser ceilometer. This technique has great advantages over other technologies and should therefore be considered as the most appropriate. Other techniques such as cloud radars and radiosonde also give information on the cloud-base height, but these systems are not cost effective when used solely for this purpose.

Note that, in addition, information on the cloud-base height is obtained from the pyrometers and micro-bolometers mentioned above as they measure the sky or cloud-base temperature. The observed temperature is affected by humidity and aerosol and requires the temperature profile in order to obtain the cloud-base height. Therefore the cloud-base height information from infrared detectors is rather poor, especially for low altitudes.

Sky imagers can give cloud-base height stereographically by viewing the same cloud with two imagers. It must be possible to identify the same specific cloud feature on both images for the technique to work correctly. The accuracy of the cloud-base height depends on the geometry that involves the distance between the imagers and the position (orientation) of the feature on both images.

### 15.4.1 Laser ceilometer measurement of cloud-base height

#### *15.4.1.1 Measurement method*

With the laser ceilometer, the height of the cloud base is determined by measuring the time taken for a pulse of coherent light to travel from a transmitter to the cloud base and to return to a receiver (principle: light detection and ranging, lidar). The output from a laser is directed vertically upwards to where, if there is cloud above the transmitter, the radiation is scattered by the hydrometeors forming the cloud. The major portion of the radiation is scattered upward but some is scattered downward and is focused in the receiver onto a photoelectric detector. The radiant flux backscattered to the receiver decreases with range according to an inverse-square law. The ceilometer (Figure 15.1) generally comprises two units, a transmitter-receiver assembly and a recording unit.

The transmitter and receiver are mounted in a single housing, together with signal detection and processing electronics. The light source is generally a semiconductor laser with a wavelength in the near infrared. The optics of the transmitter are arranged to place the laser source and receiver detector at the focus of a conventional or Newtonian telescope system. The surfaces of the lens are given a suitable quarter-wavelength coating to reduce reflection and to provide high transmission of light. The transmitter aperture is sealed by a glass window that is anti-reflection, coated on its inner surface and angled so that rain will run off it.

The receiver is of similar construction to the transmitter, except that the light source is replaced by a photodiode, and a narrowband optical filter is incorporated. The filter excludes most of the background diffuse solar radiation, thus improving the detection of the scattered laser radiation by day.

The transmitter and receiver can be mounted side-by-side so that the transmitter beam and the receiver field of view begin to overlap at about 80 m above the assembly and are fully overlapped at a few hundred metres (see for example WMO, 2016c). Cloud base detection in the blind zone below the beginning of overlap relies on return signals from the emitted pulse that have been scattered at least twice. Some systems use the same lens for the transmitted and received radiation, so that this problem is avoided.

**ELEMENT 1: Picture inline fixed size NO space**

Element Image: 8_I_15-1_en.eps

**END ELEMENT**

**Figure 15.1. Typical laser ceilometer**

The housing is provided with heaters to prevent condensation from forming on the optical surfaces, and the humidity within the housing can be reduced by the use of a desiccator. The top of the housing is fitted with a cover hood incorporating optical baffles that exclude direct sunlight.

The output from the detector is separated into sequential “range gates”, each range gate representing the minimum detectable height increment. A threshold is incorporated so that the probability of the instrument not “seeing” cloud, or “seeing” non-existent cloud, is remote.

### *15.4.1.2 Exposure and installation*

Ceilometers should be installed following the recommendations of the manufacturer. The unit should be mounted on a firm base, with a clear view overhead within a cone of approximately 30° about the vertical. If necessary, a rooftop site can be used with suitable adjustment of reported heights to ground level. Although laser ceilometers in operational use are designed to be “eye safe”, care should be taken to prevent the casual observer from looking directly into the transmitted beam. International Electrotechnical Commission (IEC) has published a set of international standards on safety of laser products (IEC 60825:2018 SER) which includes also a classification scheme according to eye safety. Eye safe laser ceilometers meeting the requirements of a class 1 or class 1M laser device as defined by this standard are commercially available.

Tilting of the instrument is necessary at some locations to prevent the sun from entering the field of view of the ceilometer. To reduce the impact of strong reflecting raindrops, the beam with the telescope can be aligned about 5° from the vertical.

### *15.4.1.3 Sources of error*

There are five main sources of error:

(a) Ranging errors: These can occur if the main timing oscillator circuits develop faults, but, in normal operation, errors due to this source can be ignored;

(b) Verticality of the transmitted/received beams: Provided that the instrument is aligned with the beam at better than 5° from the vertical, errors from this source can be ignored;

(c) Errors due to the signal-processing system: Because a cloud base is generally diffuse and varies greatly in time and distance, complex algorithms have been developed to estimate a representative cloud-base height from the returned cloud signal. In conditions of fog (with or without cloud above) and during precipitation, serious errors can be generated. Thus, it is important to have an awareness of visibility and precipitation conditions to assess the value of ceilometer information. In conditions of well-defined stratiform cloud (for example, low stratocumulus), measurement errors are controlled solely by the cloud threshold algorithms and can be assumed to be consistent for a particular make of ceilometer;

(d) Measurement range: Due to the limited power available from the laser, reflected radiation from high altitudes may have such low intensity that it cannot be detected. Therefore, cloud-base height from cirrus clouds may not always be observed.

(e) Incorrect cloud base detections: These can be caused by instrument noise. Aerosol and moist atmospheric layers can also trigger incorrect cloud base detections. Overpassing airplanes and birds, overhanging vegetation, and snow caps on the ceilometer hood can generate faulty cloud base detections.

In operational use and conditions of uniform cloud base, laser ceilometer measurements can be compared with pilot balloon ascents, aircraft measurements, visibility measurements at various altitudes up a mast or the height up to which a tower can be discerned from a camera image, and at night with cloud searchlight measurements.

Intercomparisons of laser ceilometers of different manufacturers have been carried out extensively. During the WMO International Ceilometer Intercomparison (WMO, 1988), for example, several designs of ceilometer were intercompared and comparisons made with rotating-beam ceilometers and pilot-balloon observations. The international intercomparison revealed that, using current technology, laser ceilometers provided the most accurate, reliable and efficient means of measuring cloud-base height from the ground when compared with alternative equipment.

#### ***15.4.1.4 Calibration and maintenance***

Most laser ceilometers are provided with a built-in capability to monitor the transmitted output power and the sensitivity of the detector and guard against serious timing errors. Calibration checks are normally confined to checking both the master oscillator frequency and stability, using external high-quality frequency standards and the output power of the transmitter. Calibration may also be performed by intercomparison (WMO, 1988). Some National Meteorological Services perform a field acceptance test for each ceilometer during which the cloud base detection is verified against a trusted instrument. Pointing the ceilometer to a target at a known distance (for example, a tower) can be used to confirm the distance measurement of the instrument. Routine maintenance consists typically of cleaning the exposed optics and external covers and of replacing air filters when cooling blowers are provided. Note that ceilometers generally analyse the light pulse reflected by the window in order to monitor the window contamination. Warning and alarm messages are generated that alert service staff when cleaning of the instrument is required or that the sensitivity of the instrument over the entire range might be reduced due to window contamination.

Calibration checks and routine maintenance or troubleshooting should be carried out in accordance with the manufacturer’s recommendations. Most laser ceilometers have built-in diagnostic capability to identify common faults. It is recommended that maintenance routines or troubleshooting should only be undertaken by suitably trained personnel, as hazardous voltages may be present and the laser may cause eye damage if viewed inappropriately. A ceilometer is generally designed such that precipitation runs off the window and in addition warm air is blown over the window at regular intervals to remove precipitation and leafs. Normally, little maintenance will be necessary beyond cleaning of optical surfaces and replacement of cooling fan dust filters. Snow caps on the ceilometer hood and objects or vegetation overhead the instrument should also be removed during maintenance. During inspection one has to make sure that no snow or vegetation is or will grow overhead the instrument, and that the ceilometer is not directly under the approach or take-off path of aircraft or exhaust plumes.

The range calibration may be checked in the field by comparison with cloud heights obtained using an alternative method. If cloud is not present, it is possible to point the instrument towards a solid target at a known distance. This may need to be located several hundred metres away, beyond the minimum range limit of the ceilometer. Extreme care must be taken to prevent accidental exposure to the laser beam by persons beyond the target. Some manufacturers provide a cloud simulator for verifying the operation of the ceilometer.

Modern ceilometers can make the backscatter profiles available from which the cloud base information is derived. This information is useful for verifying the correct operation of the instrument. Hence it is recommended to archive the backscatter data when possible. The data can also be used for troubleshooting, reprocessing results with optimised cloud detection algorithms and generating additional products such as mixing layer height and the detection of aerosol layers. In addition, the backscatter profile during cloud free situations can be analysed to verify the overlap correction and instrument noise characteristics that might otherwise trigger faulty cloud base detections. Furthermore, two complementary calibration methods can be used in suitable conditions for ceilometer networks with access to backscatter data. These are: (i) the so-called Rayleigh method that is based on lidar returns from purely molecular layers and is most suitable for ceilometers using photon counting detection; (ii) the so-called cloud method that is based on the full attenuation of the lidar signal in a liquid cloud and is most suitable for ceilometers with analogue detection (see WMO, 2016d).

## 15.4.2 Rotating beam ceilometer measurement of cloud-base height

### *15.4.2.1 Measurement method*

The rotating-beam ceilometer (RBC) involves the measurement of the angle of elevation of a light beam scanning in the vertical plane, at the instant at which a proportion of the light scattered by the base of the cloud is received by a photoelectric cell directed vertically upwards at a known distance from the light source (see Figure 15.2). The equipment comprises a transmitter, a receiver and a recording unit.

**ELEMENT 2: Floating object (Automatic)**
**ELEMENT 3: Picture inline fix size**
Element Image: 8_I_15-2_en.eps

END ELEMENT**Figure 15.2. A typical rotating-beam ceilometer**

**END ELEMENT**

The transmitter emits a narrow light beam of a 2° divergence, with most of the emitted radiation on the near infrared wavelengths, that is, from 1 to 3 $\mu$m. Thus, the wavelength used is small in comparison with the size of the water droplets in clouds. The light beam is swept in a vertical arc extending typically from 8° to 85° and is modulated at approximately 1 kHz so that, through the use of phase-sensitive detection methods, the signal-to-noise ratio in the receiver is improved.

The receiving unit comprises a photoelectric cell and an angle-of-view restrictor; the restrictor ensures that only light that falls vertically downwards can reach the photoelectric cell. A pen in the recording unit, moving simultaneously with the transmitter beam, records when a cloud signal is received.

### *15.4.2.2 Exposure and installation*

The transmitter and receiver should be sited on open, level ground separated by some 100 to 300 m and mounted on firm and stable plinths. It is extremely important that the transmitter scan in the same plane as the receiver. This is achieved by the accurate alignment of the optics and by checking the plane of the transmitter beam in suitable conditions at night.

### *15.4.2.3 Sources of error*

Errors in the measurement of cloud-base height using an RBC may be due to the following:

(a) Beamwidth;

(b) Optical misalignment;

(c) Mechanical tolerances in moving parts;

(d) Receiver response.

Since in most designs the volume of intersection of the transmitter and receiver cone is very significant with a cloud height above 500 m, beamwidth-induced errors are generally the most serious. The definition of cloud base given in 15.1.1 is not an adequate basis for the objective design of ceilometers, thus the algorithms in current use are based on experimental results and comparisons with other methods of estimation. Some RBCs use a “threshold” technique to determine the presence of cloud, while others use a “peak” signal detection scheme. In either case, receiver sensitivity will affect reported cloud heights, giving rise to large errors in excess of stated operational requirements in some circumstances (Douglas and Offiler, 1978). These errors generally increase with indicated height.

Rotating-beam ceilometers are very sensitive to the presence of precipitation. In moderate or heavy precipitation, the instrument can either indicate low cloud erroneously or fail to detect clouds at all. In foggy conditions, the light beam may be dissipated at a low level and the ceilometer can fail to give any useful indication of clouds, even when a low cloud sheet is present.

Comparisons of RBCs and laser ceilometers have been carried out and widely reported (WMO, 1988). These have shown good agreement between the two types of ceilometers at indicated heights up to some 500 m, but the detection efficiency of the RBC in precipitation is markedly inferior.

#### *15.4.2.4 Calibration and maintenance*

The only maintenance normally undertaken by the user is that of cleaning the transmitter and receiver windows and changing the chart. The outside of the plastic windows of the transmitter and receiver should be cleaned at weekly intervals. A soft, dry cloth should be used and care should be taken not to scratch the window. If the transmitter lamp is replaced, the optical alignment must be checked. The transmitter and receiver levelling should be checked and adjusted, as necessary, at intervals of about one year.

### 15.4.3 Searchlight measurement of cloud-base height

#### *15.4.3.1 Measurement method*

Using this method, illustrated in Figure 15.3, the angle of elevation, $E$, of a patch of light formed on the base of the cloud by a vertically-directed searchlight beam is measured by an alidade from a distant point. If $L$ is the known horizontal distance in metres (feet) between the searchlight and the place of observation, the height, $h$, in metres (feet) of the cloud base above the point of observation is given as the following:

$$h = L \tan E \qquad (15.2)$$

The optimum distance of separation between the searchlight and the place of observation is about 300 m (1 000 ft). If the distance is much greater than this, then the spot of light may be difficult to see; if it is much less, the accuracy of measuring a height above about 600 m (2 000 ft) suffers. A distance of 250–550 m (800–1 800 ft) is usually acceptable.

**ELEMENT 4: Floating object (Automatic)**

**ELEMENT 5: Picture inline fixed size NO space**

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**END ELEMENT**

**Figure 15.3. Principle of the cloud searchlight method**

**END ELEMENT**

#### *15.4.3.2 Exposure and installation*

It is desirable to have a clear line of sight between the searchlight and the alidade, both of which should be mounted on firm, stable stands. Where there is a difference in the height above the ground between the searchlight and the alidade, a correction must be incorporated in the calculated heights. If a clear line of sight is not possible, any obstruction between the searchlight beam and the alidade should not be higher than 100 feet.

#### *15.4.3.3 Sources of error*

The largest source of error is due to uncertainty in the measured angle of elevation. Height errors due to small errors of verticality are insignificant.

The absolute error $\Delta h$ in the derived cloud height due to an error $\Delta E$ in the measured elevation is given by the following ($L$ is assumed to be an accurately measured constant):

$$\Delta h = L\cdot\left(1/\cos^2 E\right)\cdot\Delta E = L\sec^2 E\cdot\Delta E \qquad (15.3)$$

with $E$ in radians ($1° = \pi/180$ rad). Note that $\Delta h$ tends to infinity when $E \rightarrow 90°$. If $L$ = 1 000 ft (300 m) and $\Delta E$ = 1°, the value of $\Delta h$ is 17 ft (6 m) when $h$ = 1 000 ft (300 m), and $\Delta h$ is about 450 ft (140 m) when $h$ = 5 000 ft (1 500 m). The relative error in $h$ is given by:

$$\Delta h/h = 1/\left(\sin E\cdot\cos E\right)\cdot\Delta E \qquad (15.4)$$

with $E$ in radians. $\Delta h/h$ is minimal when $E$ = 45° (or $h = L$).

### *15.4.3.4 Calibration and maintenance*

The focusing and verticality of the beam, should, if possible, be checked about once a month because the lamp filament is liable to undergo slight changes in shape with time. When a lamp is replaced, the adjustment for lamp position should be carried out since not all lamps are identical.

The verticality of the beam should be checked during an overcast night with the aid of a theodolite. The check should be made from two positions, one near the alidade and the other at about the same distance away from the searchlight in a direction at right angles to the line joining the searchlight and the alidade (Figure 15.4). The azimuths of the searchlight and of the spot of light on the cloud should be measured as accurately as possible, together with the elevation of the spot of light. If the difference between the azimuth readings is $A$ and the angle of elevation is $E$, the deviation $\phi$ of the beam from the vertical is given by:

$$\begin{gathered}\phi = \arctan\left(\tan A/\tan E\right) \approx A/\tan E \\ \left(\text{for } A \approx 1° \text{ or less}\right)\end{gathered} \qquad (15.5)$$

If the value of $\phi$ is more than 1° when viewed from the alidade, or more than 0.5° in the other position, these adjustments should be repeated until the necessary accuracy is obtained.

Focusing can be checked and adjusted on an overcast night by observing the diameter of the light spot on the highest cloud above the instrument. If necessary, the focus should be adjusted to minimize the spot diameter.

**ELEMENT 6: Floating object (Bottom)**
**ELEMENT 7: Picture inline fix size**
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**END ELEMENT**

**Figure 15.4. Checking the verticality of the searchlight beam**

**END ELEMENT**

## 15.4.4 Balloon measurement of cloud-base height

### *15.4.4.1 Measurement method*

Cloud height may be measured in daylight by determining the time taken by a small rubber balloon, inflated with hydrogen or helium, to rise from ground level to the base of the cloud. The base of the cloud should be taken as the point at which the balloon appears to enter a misty layer before finally disappearing.

The rate of ascent of the balloon is determined mainly by the free lift of the balloon and can be adjusted by controlling the amount of hydrogen or helium in the balloon. The time of travel between the release of the balloon and its entry into the cloud is measured by means of a stop-watch. If the rate of ascent is $n$ metres per minute and the time of travel is $t$ minutes, the height of the cloud above ground is $n \cdot t$ metres, but this rule must not be strictly followed. Eddies near the launch site may prevent the balloon from rising until some time after it is released. Normally the stop-watch is started on the release of the balloon and, therefore, the elapsed time between when the balloon is released and the moment when it is observed to have left the eddies will need to be subtracted from the total time before determining the cloud height. Apart from eddy effects, the rate of ascent in the lowest 600 m (2 000 ft) or so is very variable.

Although the height of the base of a cloud at middle altitude is sometimes obtained as a by-product of upper wind measurements taken by pilot balloons, the balloon method is mainly applicable to low clouds. Where no optical assistance is available in the form of binoculars, telescope or theodolite, the measurement should not be attempted if the cloud base is judged to be higher than about 900 m (3 000 ft), unless the wind is very light. In strong winds, the balloon may pass beyond the range of unaided vision before it enters the cloud.

Precipitation reduces the rate of ascent of a balloon and measurements of cloud height taken by a pilot balloon should not be attempted in other than light precipitation.

This method can be used at night by attaching an electric light to the balloon. For safety reasons, the use of candle lanterns is strongly discouraged.

#### *15.4.4.2 Sources of error*

Measurements of cloud base taken using a height balloon must be used with caution, since the mean rate of ascent of a balloon, especially in the first few hundred metres, may differ appreciably from the assumed rate of ascent (owing to the effects of vertical currents, the shape of the balloon, precipitation and turbulence).

## 15.5 INSTRUMENTAL MEASUREMENT OF CLOUD TYPE

Observation of cloud type is still generally performed by human observers. One automatic method to observe cloud type is used operationally, which is specifically for detecting cumulonimbus/towering cumulus for aeronautical applications. In this method, data from a precipitation radar and lightning detection network are used. The radar-reflectivity classes and the number of lightning discharges within a certain area are combined to give information on the presence of cumulonimbus and/or towering cumulus. This is a new method which is used by a few Meteorological Offices. The false alarm rate is relatively high (see WMO, 2006*b*). Some offices use satellite (VIS and IR channels) and model information to enhance the CB/TCU product.

The derivation of cloud type by considering several statistical spectral and textural features of the camera image is under development. The success rate is promising for homogenous cases (75-88 %), but lower in case of mixed scenes (see for example, Heinle et al., 2010 and Liu et al., 2011).

## 15.6 OTHER CLOUD-RELATED PROPERTIES

### 15.6.1 Vertical visibility

Vertical visibility is defined as the maximum distance at which an observer can see and identify an object on the same vertical as him/herself. It can be calculated from the extinction profile of the atmosphere. Ceilometers (see 15.4.1 and 15.4.2) may provide an estimate of vertical visibility, based on the integrated extinction profile with range (see equation 15.1). WMO (1988) showed that this method frequently produces unreliable results. In practice, a vertical visibility report is often given by a ceilometer when the cloud-base requirements are not met, but when reflected light is received from a certain altitude.

Chapter title in running head: CHAPTER 15. OBSERVATION OF CLOUDS
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Part title in running head: PART I. MEASUREMENT OF METEOROLOGICAL VARI…

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