EFFORTS TO DEVELOP A QUANTITATIVE DEFINITION OF CLOUD BASE HEIGHT FOR AVIATION

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ABSTRACT

Ceilometers are established measuring instruments for determining cloud base height (CBH) from the attenuated lidar backscatter signal. However, due to the application of manufacturer-specific algorithms and the lack of a generally accepted quantitative definition for clouds, various types of ceilometers derive different CBHs for the same cloud situation. This is particularly important for air traffic control in low cloud situations.

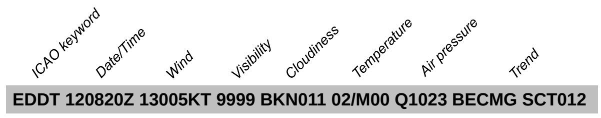
In the framework of the project “AutoMETAR” initiated by Deutscher Wetterdienst (DWD) and in collaboration with the Universität Hamburg, an experiment was set-up to use the 300 m high “Hamburg Weather Mast” to investigate a visibility based definition of CBH based on image analysis. For the 1st phase of the so-called CircaHH campaign (10/2016 – 04/2017) a digital camera was installed 178 m away from the mast. Since the latter is increasingly obscured from the top downwards if the CBH descends, the contrast ratio of its alternating red and white segments has been used to calculate the vertical profile of the extinction coefficient. A number of different methods were analyzed for their suitability to derive CBH from these profiles. The slant optical range (SOR) was found to be the most appropriate quantity, with CBHs calculated using a SOR threshold of 1000 m showing the best agreement with those estimated visually. Furthermore, they also agreed well with CBHs provided by the Vaisala ceilometer LD40, which is currently used at German international airports.

During the 2nd phase of CircaHH in 2018 data of two visibility sensors installed in 175 m and 280 m altitude will be used to verify the extinction profiles derived from the digital images.

Our preliminary results suggest that a SOR using a threshold of 1000 m can serve as an adequate quantitative definition of CBH. This definition can also be applied to extinction profiles derived directly from backscatter signals of ceilometers.

1. MOTIVATION

METAR is the acronym for Meteorological Aviation Report, which is created and provided for pilots, meteorological consultants, and especially for flight controllers, who coordinate the air emergency and air traffic in general. Its first entry is the keyword of the International Civil Aviation Organization (ICAO) as identifier for the airport. In the following example “EDDT” is associated with the German international airport Berlin Tegel.



The meaning is written above a respective report group. Most of these report groups are created already automatically, except for those referring to cloudiness and recent weather. Their automation at German international airports is the aim of the AutoMETAR project. In our subproject the focus is on the cloudiness report group that includes information about the cloud coverage, determined in oktas but assigned to acronyms (e.g. BKN = broken for 5/8–7/8), as well as CBH in hecto feet (1 hft = 100 ft). In this study, the automation of CBH is discussed in more detail.

The determination of the CBH information requires a measuring instrument. For this purpose a ceilometer is used, which is a compact and inexpensive Light Detection And Ranging (LIDAR) device for deriving CBH from the measured attenuated backscatter signal. Its name originates from the word “ceiling”. The measuring principle is relatively simple: Laser pulses are emitted vertically and the photons are scattered by cloud particles. The light that is scattered in the backward direction can be detected by the receiving unit. CBH can basically be calculated from the time that passes between the emission of the laser pulses and detection of the attenuated backscatter signal. However, it is much more complicated and the ceilometer actually measures the vertical profile of the backscattered power $P(r)$, where r is the range. After reformulation of the LIDAR equation for single-scattering the vertical profile of the attenuated backscatter coefficient

$$\beta_{\mathrm{att}}(r) = \frac{P(r)\, r^2}{C_{\mathrm{L}}\, O(r)} \quad (1)$$

can be obtained. In Eq. (1) C_{L} represents the LIDAR constant and $O(r)$ the so-called overlap function.

The vertical profile of uncalibrated $\beta_{\mathrm{att}}(r)$ is usually provided by different manufacturers and can be used to derive CBH. A problem arises because each manufacturer uses another optical configuration and applies its own corrections. This can be demonstrated with the example of $O(r)$. Despite the different location of the transmitting and receiving units there is always an incomplete overlap between the laser beam and the receiver's field of view leading to defective measurements in lower altitudes that need to be corrected by $O(r)$. However, this function is significantly different for various ceilometer types although the co-domain is basically between 0 and 1.

An additional problem arises due to the application of different and proprietary algorithms to derive CBH from the profile of $\beta_{\mathrm{att}}(r)$. The combination of different $\beta_{\mathrm{att}}(r)$ profiles and different definitions for CBH results in significant differences in the provided CBH of about 300 ft (90 m). This has already been found during the CeiLinEx2015 campaign (see Fig. 1).

Currently, two types of ceilometers are used by DWD: The LD40 from the company Vaisala and the CHM15k from LUFFT. There are 165 ceilometers at 165 synoptic weather stations and even 51 ceilometers (only LD40) at 16 German international airports. The larger number of ceilometers at the airports is due to the number of runways and thresholds. Furthermore, additional ceilometers will be installed to increase the representativity and accuracy of the cloud detection. At the end of the AutoMETAR project 97 ceilometers will be located at the airports and in addition all devices will be replaced by a new ceilometer type. In the frame of the new procurement of ceilometers there is a need for a ceilometer type-independent CBH definition.

Thus, the lack of a generally accepted definition for CBH was the starting point for the "**Cei**lometer **ca**mpaign **H**ansestadt **H**amburg" (CircaHH).

2. EXPERIMENTAL SETUP

CircaHH was a collaboration between DWD and the universities of Leicester and Hamburg. During this measuring campaign a Sony Alpha 7 digital camera took photos of the 300 m-heigh "Hamburg Weather Mast" from October 2016 to April 2017. This allowed the observation of very low-lying clouds and the aim was to evaluate the 4 ceilometers (LD40 and CL31 from Vaisala, CHM15k from LUFFT, and CS135 from Campbell) installed close to the weather mast. All measuring instruments are illustrated in Fig. 2.

The camera was installed 178 m away from the weather mast. If CBH was smaller than 500 m then a photo was taken every minute and otherwise every 10 minutes. This criterion was applied based on the lowest CBH derived by the 4 ceilometers used here. The series of photos can be used either for visual verification or as the basis of an image analysis.

3. QUANTITATIVE DEFINITION OF CBH

The image analysis used in this study starts with the calculation of the contrast ratio (Michelson contrast), which is the ratio between the intensities of the red and white segments of the weather mast. This ratio is determined for conditions without very low clouds and unrestricted visibility ($C_0 = I_{\mathrm{r0}}/I_{\mathrm{w0}}$) and when the weather mast is partly obscured by clouds ($C = I_{\mathrm{r}}/I_{\mathrm{w}}$). Then, the vertical profile of the extinction coefficient can be calculated by use of the following formula

$$\sigma(h) = \frac{\ln\left(\frac{C}{C_0}\right)}{d} \quad , \quad (2)$$

where h is the height and d the distance between a respective mast segment and the camera. A number of different methods were analysed for their ability and effectiveness to derive CBH from the extinction profiles obtained by the above-mentioned image analysis. For instance, the meteorological optical range

$$\mathrm{MOR} = -\frac{\ln(0.05)}{\sigma(h)} \approx \frac{3}{\sigma(h)} \quad (3)$$

with a typical contrast ratio of 5 % was checked. It represents the horizontal visibility and is already applied by some ceilometer manufacturers. However, the slant optical range

$$\mathrm{SOR} = H\sqrt{\left(\frac{3}{\int_0^H \sigma(h)\mathrm{d}h}\right)^2 - 1} \quad (4)$$

was found to be the most suitable quantity.

From the geometric point of view SOR is the projection of a slant line of vision onto the horizontal plane. By comparing Eq. (3) and (4) it becomes obvious that only SOR takes into account the visibility below cloud base. In particular, it is realized by the integral of σ over height. On the other hand, a threshold value is necessary to assign CBH. In case of MOR 1000 m is typically used. Now let's assume good visibility below cloud base and the same threshold value of 1000 m for SOR. Then, CBH calculated based on SOR is larger than compared to the value based on MOR. That behaviour is absolutely realistic and reasonable, because the cloud base is diffuse and an observer at the ground can see a bit into the cloud if there is no obscuration in between. In contrast,

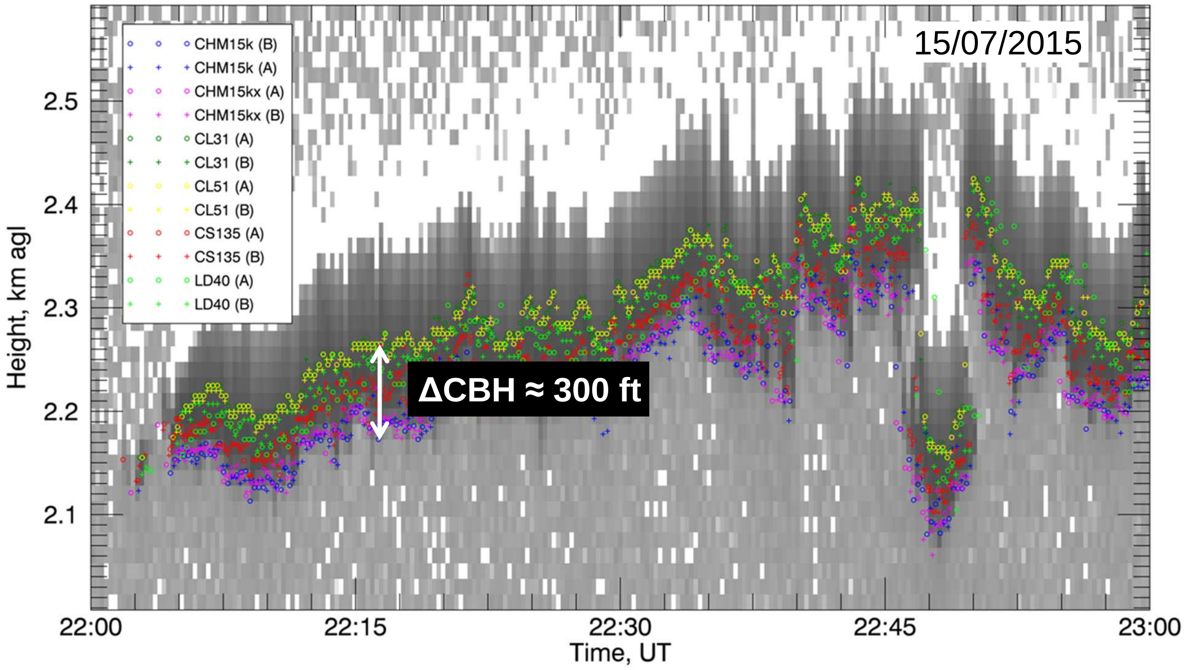


Figure 1. Temporal evolution of cloud base height (CBH) for Stratocumulus derived by various ceilometer types and configurations (see table 1 by [1]) from 22 UTC to 23 UTC on July 15, 2015. The gray-shaded areas illustrate the attenuated backscatter signal of the CHM15k (B) from LUFFT.

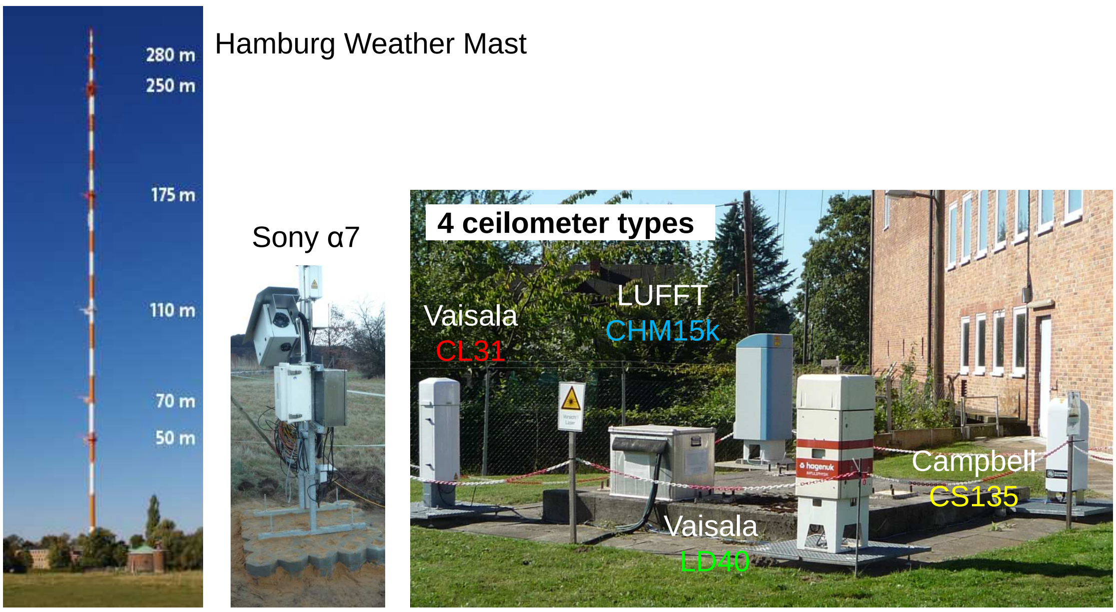


Figure 2. Measuring instruments used during the 1st phase (10/2016 – 04/2017) of the CircaHH campaign.

if the visibility below cloud base becomes worse then the extinction coefficient increases in this height range. While CBH based on SOR would realistically decrease the CBH based on MOR would remain unchanged. Thus, SOR with a threshold value of 1000 m is used as quantitative definition for CBH.

4. RESULTS

Figure 3 shows the results exemplarily for November 12, 2016. CBHs calculated by our SOR definition (red curve) agree qualitatively with those derived by the ceilometer types LD40 (green curve) and CHM15k (blue curves). The differences between the light and dark blue curves can be explained by the application of two different firmware versions. The newer firmware version v0747 of CHM15k uses a modified cloud detection algorithm to avoid unrealistic near-surface clouds and to provide systematically larger CBH values (see 9:00−10:30 UTC in Fig. 3).

The qualitatively best agreement between the red and green curves means that despite the application of totally different methods our SOR definition produces similar CBHs as the ceilometer type LD40 from Vaisala. The latter is particularly important, because pilots and meteorological consultants are familiar with CBHs provided by this ceilometer type currently used at German international airports. The comparison to the photos (bottom row of Fig. 3) suggests that the up and downs (temporal evolution) and even the absolute values of CBH seem to be derived correctly by our SOR definition.

As final step our SOR criterion was applied to the vertical profile of $\sigma(h)$ derived directly from the backscatter signal of the ceilometer by means of the Klett algorithm [2]. We have programmed our own formulation using the theory by [3] with improvements suggested by [4]. As soon as $\sigma(h)$ is known the SOR definition can be applied similarly to the image analysis. This method to derive CBH is still under development so that only preliminary results can be presented.

In Fig. 3 the corresponding CBHs are shown by the purple curve. Its qualitative agreement to the other curves is fairly well at least after 10:45 UTC. The visual verification based on the photos indicates a dissolving surface-based fog layer before 10:45 UTC and the more pronounced fluctuations in the purple curve reflect reality, because a fog layer is rarely horizontal homogeneous. Furthermore, the visual verification reveals that only the purple curve correctly describes the conditions around 13:15 UTC when CBH is obviously larger than 175 m (see Fig. 4).

5. CONCLUSIONS AND OUTLOOK

Both the differences in the vertical profile of the attenuated backscatter coefficient provided by various manufacturers and the application of proprietary algorithms due to the lack of a generally accepted definition are serious problems impeding the determination of distinct and reliable values of cloud base height (CBH).

The novel and unique results based on the measurements carried out during the 1st phase of the CircaHH campaign presented here suggest that:

- The slant optical range (SOR) with a threshold value of 1000 m appears to be a suitable quantitative definition for CBH.
- The image analysis can provide a reference method to evaluate CBHs obtained from various ceilometer types.
- The combination of the Klett algorithm and SOR criterion offers a physically motivated method to determine CBH.

For the 2nd phase of CircaHH two visibility sensors (PWD20) were installed in 175 m and 280 m height at spring 2018. Their measurements should help to verify the extinction profiles derived from the image analysis.

6. ACKNOWLEDGEMENTS

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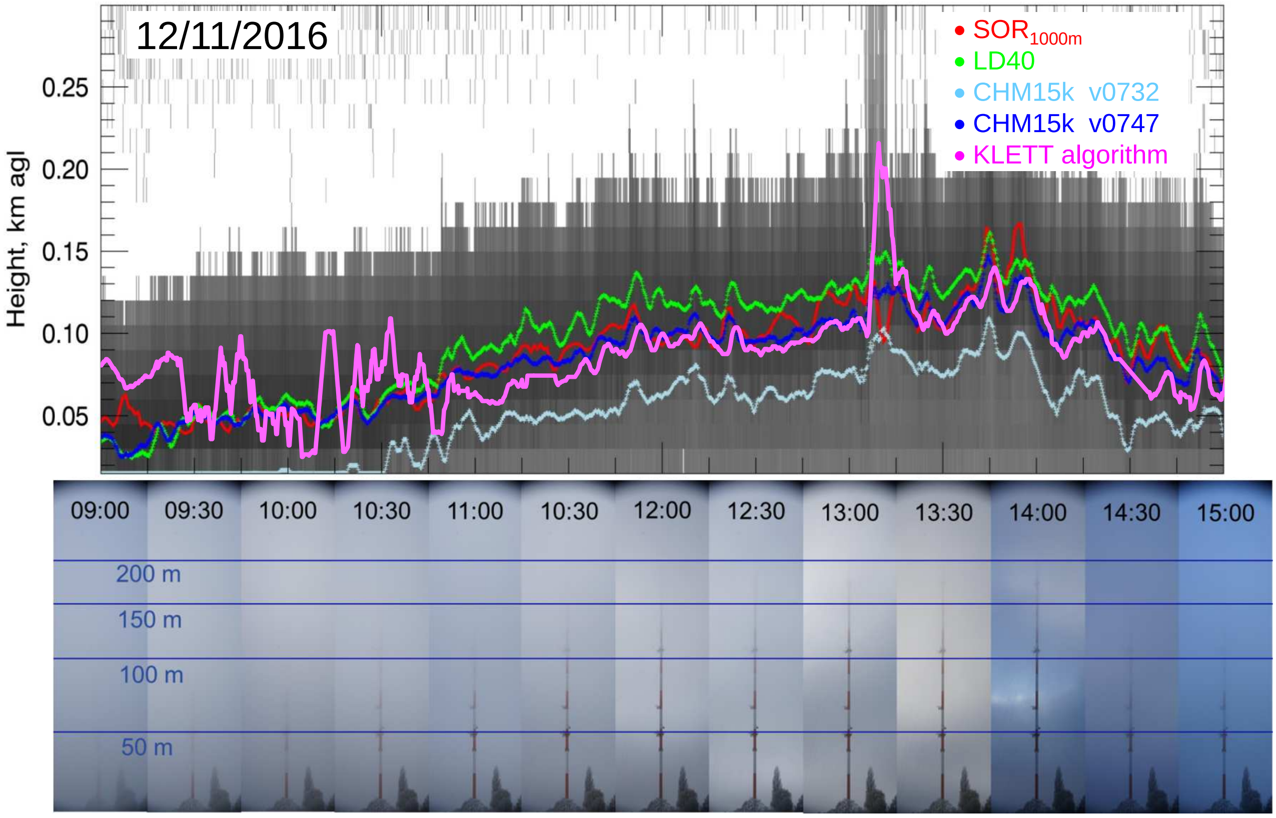

Figure 3. Top row: Temporal evolution of cloud base height (CBH) derived by the ceilometer types LD40 (green) from Vaisala and CHM15k from LUFFT with two different firmware versions v0732 (light blue) and v0747 (dark blue), and additionally by use of the slant optical range (SOR) definition applied to the extinction profiles derived from either image analysis (red) or the Klett algorithm based on CL31 backscatter profiles (purple). Bottom row: Photos of the Hamburg Weather Mast taken by the Sony Alpha 7 camera with added horizontal lines for easier visual verification. Results are shown from 9 UTC to 15 UTC on November 12, 2016.

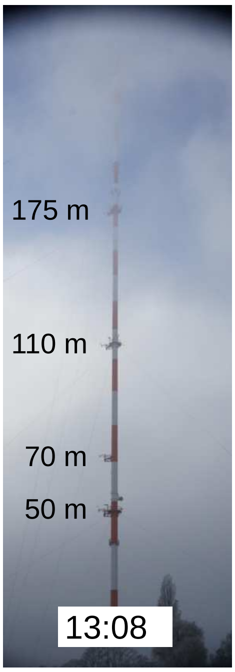

Figure 4. Photo of the Hamburg Weather Mast taken by Sony Alpha 7 camera on November 12, 2016 at 13:08 UTC.