Introduction to Ceilometer: Instrumentation and Data Interpretation

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Atmospheric Lidar Group

Abbreviations and Acronyms

AMS	American Meteorological Society
CCN	Cloud Condensation Nuclei
EPA	Environmental Protection Agency
Lidar	Light Detection and Ranging
ML	Mixing Layer
MLH	Mixing Layer Height
NOAA	National Oceanic and Atmospheric Administration
NSBL	Nocturnal Stable Boundary Layer
PAMS	Photochemical Assessment Monitoring Stations
PBL	Planetary Boundary Layer
RL	Residual Layer
SIP	State Implementation Plan

Contents

1.0 Ceilometer: Atmospheric Lidar

Ceilometer is a device for determining the cloud ceiling by means of a reflected light beam. The American Meteorological Society (AMS) defines cloud ceiling as the height of the lowest opaque cloud layer.[1] Therefore, the word originating from "ceil(ing)-o-meter". The invention of the ceilometer is attributed Denmark's first graduate meteorologist Poul la Cour. The first ceilometers used light rays from floodlights that were directed at the bottom of clouds. The spot on the cloud base allowed to triangulate up to the height of the cloud base.[2]

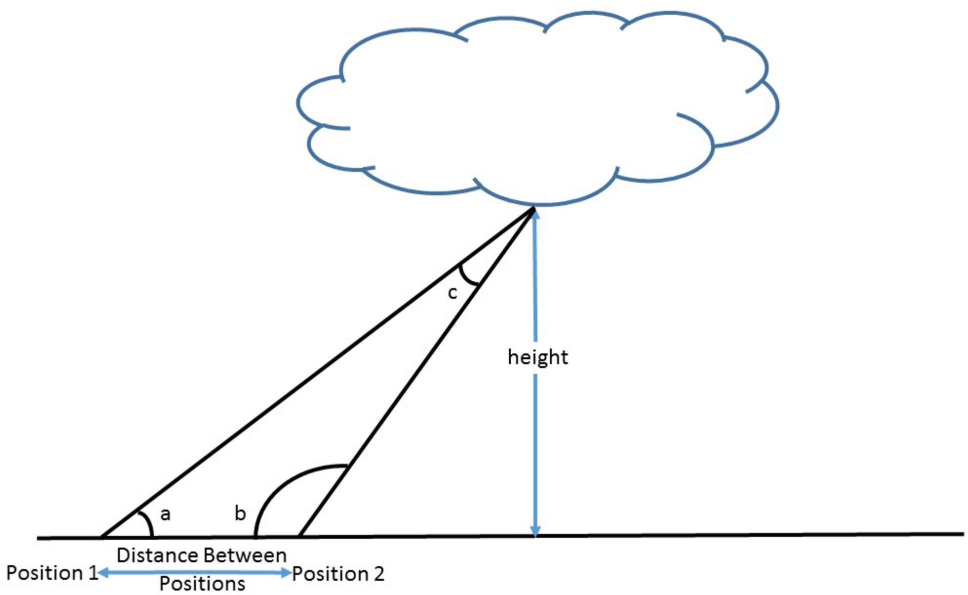

Figure 1. Illustration of height measurement using triangulation. If angles a, and b are known, as well as the distance between positions, then trigonometry can be used to obtain the cloud height (h).

When the light source is based on laser technology, the ceilometer is then a type of atmospheric lidar. *Lidar* in the acronym for *li*ght, *d*etection *a*nd *r*anging, was developed as a remote sensing technique in the early 1960's, with the first measurements made a year after laser were invented.[3] Lidars are used to precisely measure distances and properties of distant objects. The performance of a lidar system, such

[1] American Meteorological Society, cited 2020: Cloud Ceiling. Glossary of Meteorology. [Available online at http://glossary.ametsoc.org/wiki/climatology.]
[2] Pagh Nielsen, K., Poul la Cour –og ceilometret, Verjet (153), 24-26, 2017.
[3] Fiocco, G.L. and Smulin, L; Detection of Scattering Layers in the Upper Atmosphere by Optical Radar, Nature (199), 1275-1276, 1963.

as modern commercial ceilometers, relies on how efficiently a photon can travel through the atmosphere and return to its point of origin. The returning photons are counted as a function of time and using the speed of light one can determine the distance traveled by the photons. The range (distance traveled by the photons), R, can be determined by the time of flight of the photons through Equation 1:

$$R = c\frac{\Delta t}{2} \qquad (1)$$

where c is the speed of light, Δt is the time of flight, and the number 2 accounts for the round trip of photons traveled.

Lidar has many advantages over other forms of remote sensing. First and foremost, lidar can produce profiles of the atmosphere over very short time scales. This feature is valuable when studying atmospheric phenomena that change on short time scales. Lidar is also capable of producing profiles with very high vertical resolution, having resolution on the order of 5 to 30 meters. In contrast, passive systems can only retrieve the total atmospheric column or coarse vertical profiles. This high temporal and spatial resolution are especially helpful in aerosol (particle pollution) and cloud studies when studying the evolution of specific layers in the atmosphere, since significant changes in atmospheric properties can occur over periods of a minute or less and over distances of few tens of meters. Another advantage of using lidar as a remote sensing tool includes the unobtrusive nature of the probing which doesn't contaminate the measured parcel of air and the option of integrating layer-specific stratified data into column density information.

2.0 Theory

a. Scattering Theory

Light scattering and absorption enable the ceilometer to conduct lidar remote sounding. By understanding the fundamentals of these processes, it is possible to extract information from the ceilometer backscatter profiles. Scattering and absorption effects fall into major categories: elastic regime, the case for which the backscattered light is the same frequency as the outgoing laser light, and the inelastic regime in which the light experiences a frequency shift as a result of an interaction with particles or molecules in the atmosphere. The scope of this manual lies solely in the discussion of elastic scattering, the regime of scattering in which ceilometers systems operate.

b. Types of Scatters

The atmosphere consists of many particles. These particles can range in size from single atoms to large particulate masses. There is also a variation in the composition of these particles from pure molecular and atomic species to complex organic molecules. The majority of scatter in the atmosphere consists of diatomic nitrogen (N_2) and oxygen (O_2) molecules, accounting for 78% and 21% of the total number density in the atmosphere, with the remainder made up of trace gases such as water vapor, carbon dioxide, argon and methane.[4]

Aerosols are defined as a system of colloidal particles dispersed in gas. Concentrations generally are smallest over the oceans and greatest over metropolitan and industrialized areas. Typical number density concentrations are 10^3 cm^{-3} over oceans, 10^4 cm^{-3} over land, and 10^5 cm^{-3} over urban areas. Urban aerosols can be classified into three categories based upon size. Particles with a diameter of less than 0.1 µm are generally referred to as particles in nuclei mode, particles from 0.1 to 2.5 µm in diameter are referred to as particles in accumulation mode, and particles above 1.0 µm are in coarse-particle mode.

Nuclei mode (particle size < 0.1 µm) consists primarily of combustion particles emitted directly into the atmosphere and particles formed in the atmosphere by gas-to-particle conversion. They are usually found near highways and other sources of combustion. Because of their high number concentration, especially near their source, these small particles coagulate rapidly. Consequently, nuclei particles have relatively short lifetimes as Brownian motion causes collisions and the growth of larger particles through a process known as coagulation. Coagulation times vary as a function of particle diameter, but on average lie close to 10^{-3} seconds. Accumulation mode (0.1 µm $<$ particle size $<$ 2.5 µm) includes combustion particles, smog particles, and coagulated nuclei-mode particles. The smog particles are formed in the atmosphere by photochemical reactions. Particles in this mode are small but they coagulate too slowly to reach the coarse-particle mode. Hence, they have a relatively long lifetime in the atmosphere, and they account for most of the visibility effects of atmospheric aerosols. The nuclei and accumulation modes together constitute “fine” particles. The coarse-particle *mode* (particle size $>$ 2.5 µm) consists of windblown dust, large salt particles from sea spray, and mechanically generated anthropogenic particles such as those from agriculture and surface mining. Because of their large size, the coarse particles readily settle out or impact on surface, so their lifetime in the atmosphere is only a few hours.[5]

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[4] Wayne, R.P.; Chemistry of the Atmosphere; 2nd Ed., Oxford University Press, London, 1991.
[5] Finlayson-Pitts, B. J. and Pitts, J. N. J.; Chemistry of the Upper and Lower Atmosphere; Academic Press: New York, 2000.

Aerosol play direct role in the formation of clouds, acting as Cloud Condensation Nuclei (CCN) for cloud development. The most effective CCN's are hygroscopic in nature, meaning the size of the particles increase with increasing humidity due to water absorption. Clouds are produced by heterogeneous nucleation; the process in which water vapor condenses on aerosol particulates, producing either cloud droplets or ice particles, depending on the temperature. The average water cloud droplet size lies between 2 and 29 µm, while ice clouds may have crystals with lengths on the order of 18 to 300 µm.[6]

All these particles act as light scatters, such that each particle scatters incident light in a way dependent upon the size, shape, and type (material/composition) of the particle. Since particles exist in such a wide variety of sizes, shapes, and materials, several considerations must be used when attempting to understanding scattering processes. The elastic scattering mechanisms of interest are Rayleigh and Mie scattering. Rayleigh scattering, best known for the blue skies and red sunsets, is considered an elastic scattering process in which the incident light interacts with air molecules. Mie scattering occurs when the particles are approximately the same size as the wavelength of the scattering light. Extensive discussions of these scattering processes can be found in the literature.[7] The derivation of the Rayleigh and Mie scattering is extremely lengthy and falls out of the scope of this manual.

3.0 Principle of Operation

The ceilometer consists of the same components characteristic of many elastic backscatter lidars. These components can be organized into basic categories consisting of a transmission stage that includes the laser and steering optics, and receiving stage which includes a telescope, detectors, optics and processing stage which consist of a digitizer, software and storage device.

The transmission stage (Figure 2) in commercial ceilometers consists of pulsed laser usually emitting radiation in the near-infrared (900-1064 nm) region of the electromagnetic spectrum, with mirrors (optics) coated for optimal transmission of the laser light. To guarantee that the emitted laser light complies with eye-safety requirements the laser power is downgraded using neutral density filters

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[6] Pandis, S. and Seinfeld, J. H.; Atmospheric Chemistry and Physics: Form Air Pollution to Climate Change, 2nd Ed., John Wiley & Sons, New York, 2006.
[7] Measures, R.; Laser Remote Sensing: Fundamentals and Applications, Wiley-Interscience, New York, 1984.

or beam expanders. The beam expander is an optical device that increases the laser beam diameter while decreasing beam divergence (spread).

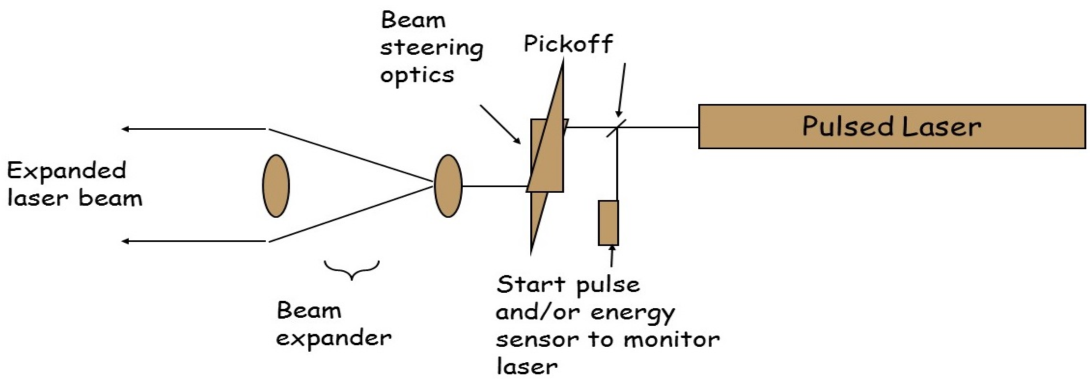

Figure 2. Simple diagram of ceilometer transmitter.

The receiver stage (Figure 3) consists of a telescope, optics (mirrors, filters to reduce sky/sunlight background and optics to collimate light), photodetector and electronics to digitize and process the returning laser photons to obtain the aerosol backscatter profile.

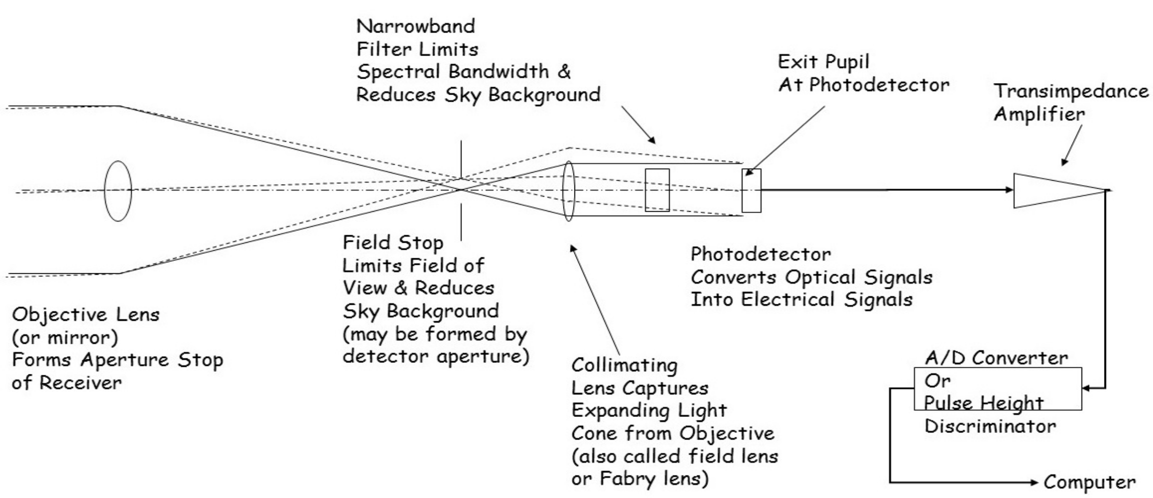

Figure 3. Simple diagram of ceilometer receiver.

a. Lidar Equation

The lidar equation for elastic backscattering describes how the received signal, P, depends on atmospheric parameters and range z:

$$P(z) = K \frac{\beta(z)}{z^2} e^{-\int_0^z \alpha(z)dz} \qquad (2)$$

where K is the system constant, α and β are the extinction and backscatter coefficient, respectively. The extinction and backscatter coefficient consider the contributions of particles and molecules.

In the formulation of the lidar equation it is assumed that only single scattering occurs (a photon is scattered only once) and that scattering processes are independent. Independent scattering means that particles are separated adequately and undergo random motion so that the contribution to the total scattered energy by many particles (intensity) is simply the sum of the intensity scattered from each particle. A thorough derivation for aerosol backscatter from ceilometers can be found in Wiegner et al. (2014).[8]

4.0 Atmospheric Research Applications

The presence of particle pollution in the atmosphere and their extension on a given air mass can be determined from the ceilometer data. This provides a comprehensive three-dimensional assessment of the atmosphere by coupling surface measurements; ceilometer and satellite observations that can aid future policy decisions and strategies as key questions on the influence of gases and aerosols in air quality, atmospheric composition and climate are addressed. Ceilometer networks have been typically established by national weather services around the globe primarily designed for detection of clouds. The instrument capability of providing observations of the vertical structure of the boundary layer makes it a resourceful tool to study atmospheric phenomena. Beyond the monitoring of cloud base height and vertical visibility, ceilometers have been used for several research applications including the study of signatures of different types of precipitation.[9] The most important extended application, however, is the retrieval of aerosol properties. Ceilometers often lack the stability and sensitivity of more refined instruments and typically have one elastic channel only. For these reasons, the aerosol-related parameter most realistic for study using ceilometers is the height of the planetary boundary layer (PBL).

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[8] Wiegner et al.; What is the benefit of ceilometers for aerosol remote sensing? An answer from EARLINET, Atmospheric Measurements Techniques, 7, 1979-1997, 2014

[9] Müenkel,C.; Rain-snow discrimination with a biaxial lidar ceilometer, Proceedings Vol. 5059, 12th International Workshop on Lidar Multiple Scattering Experiments, 160-170, 2003.

As the PBL contains the majority of the atmosphere's aerosols and its height can be found by locating the first significant decrease in lidar return intensity. The PBL height is variable in time and space, ranging from hundreds of meters to a few kilometers. It is a key parameter in the description of vertical processes in the lower troposphere and an important input parameter in air quality models. The PBL typically has much higher concentration of aerosols than the troposphere above it, and thus it provides a stronger backscatter signal in ceilometer measurements. Note, however, that "boundary layer height" reported by this method is the height of the top of the aerosol layer closest to the surface. Wavelet filtering techniques, which locate features in a signal using filters based on families of wavelet functions[10], have also been applied to identify the top of the boundary layer from return signals from ceilometers[11] [12].

Ceilometers can provide two basic quantities for applications: the geometrical thickness (variation of space/height and time) of a semi-transparent backscattering (lofted) layer and its height above the ground level. These semitransparent layers consist of particle pollution (aerosol, smoke, dust, volcanic ash). The autonomous operation (24/7) capability of ceilometers is important to the aviation communities. Plumes of volcanic ash near active volcanoes are a flight safety hazard, especially for night flights. Volcanic ash is hard and abrasive and can quickly cause significant wear to propellers and blades, and scratch cockpit windows, impairing visibility. The European lidar network and the Deutscher Wetterdienst Department (DWD - German Weather Service) has demonstrated the utility of network ground based lidar instruments during the 2010 Eruption of the Eyjafjallajökull.[13] The 24/7 operational capability of a ceilometer network is extremely useful for the air quality community. Full-range backscatter profiles measured by ceilometers can allow for the identification and potential justification of an air quality exceptional event.

The U.S. Environmental Protection Agency (EPA) requirement to state and local air quality agencies to measure hourly mixing layer height (MLH) at the national Photochemical Assessment

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[10] Brooks, I.M.; Finding boundary layer top: Application of a wavelet covariance transform to lidar backscatter profiles, J. Atmos. Oceanic Technol., 20 (8), 1092-1105, 2003.
[11] Caicedo et al.; Comparison of aerosol lidar retrieval methods for boundary layer height detection using ceilometer aerosol backscatter data, Atmos. Meas. Tech., 10, 1609-1622, 2017.
[12] Hicks, et al.; Intercomparison of Mixing Layer Heights from the National Weather Service Ceilometer Test Sites and Collocated Radiosondes, J. Atmos. Oceanic Technol., 36, 129-137, 2019.
[13] Flentje, H., Heese, B., Reichardt, Thomas, W.; Aerosol profiling using the ceilometer network of the German Meteorological Service. Atmos. Meas. Tech. Disc., 3, 3643-3673, doi: 10.5194/amtd-3-3643-2010.

Monitoring Stations (PAMS), will be the first concerted effort to use the ceilometer aerosol profiles for the determination of MLH in the PBL. The primary purpose for the hourly MLH under PAMS was driven by the state's State Implementation Plan (SIP) modeling data needs. The PAMS requirement to measure the MLH is not limited to a particular technology and will likely be meet through the deployment of a combination of sophisticated instrumentation (ceilometers, lidars, Doppler wind lidars and radar wind profilers). A first step to developing a "network of networks" is to develop a common MLH algorithm that can be implemented across a heterogeneous network which includes ceilometer/lidars. Hence, centralized standardization of data outputs and retrievals are needed. A unique automated PBL retrieval algorithm was created by Caicedo et al. (2020)[14] as a common cross-platform method for use with commercially available ceilometers for implementation under the redesigned U.S. EPA PAMS program. This algorithm addresses instrument signal quality and screens for precipitation and cloud layers before the implementation of the retrieval methodology using the Haar wavelet covariance transform method. Layer attribution for the PBL height is supported with the use of continuation and time-tracking parameters, and uncertainties are calculated for individual PBL height retrievals.

MLH can be used for the validation of different PBL parametrizations in meteorological, chemical and forecasting models. A common element to model validation activities is the transformation of prognostic (e.g. mass mixing ratios for several aerosol components) to measured variables (e.g. optical aerosol properties). Quantitative range-resolved aerosol parameters can be obtained from advanced lidar measurements that are expensive in investment and maintenance. Ceilometers emerge as an option because they can operate continuously, are fully automated and eye safe. The ceilometer primary output is attenuated aerosol backscatter, and mathematical inversions of their signals can provide the particle backscatter coefficient if the lidar ratio (extinction to backscatter ratio) is known. Chan et al.[15] demonstrated that ceilometer networks can offer several options for the validation of numerical models besides the vertical attenuated backscatter. Ceilometers allow for the verification of altitude, extent, temporal development and mean particle backscatter of extended/elevated aerosol layers. In addition, they indicate that ceilometer networks might be the observational backbone needed for model validation.

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[14] Caicedo et al.; An automated common algorithm for planetary boundary layer retrievals using aerosol lidars in support of the U.S. EPA Photochemical Assessment Monitoring Sites Program. J. Atmos. Oceanic. Technol., 1-51, DOI: 10.1175/JTECH-D-20-0050.1, 2020.

[15] Chan et al., Evaluation of ECMWF-IFS (version 41R1) operational model forecasts of aerosol transport by using ceilometer network measurements, Geosci. Model Dev., 11, 3807-3831, 2018.

5.0 Interpreting Ceilometer Data

a. Planetary Boundary Layer

Ceilometers are powerful tools for visualizing aerosol distribution, cloud-top altitudes, and pollution transport in the PBL. Ceilometer data is typically depicted with time series using logarithmic color scales to account for the large range of aerosol backscatter measurements. Figure 4 is a time series plot of data from a ceilometer with altitude in kilometers on the y-axis and time in Universal Coordinated Time (UTC; EST = UTC-5) on the x-axis. The images are color-coded, with reds and yellows corresponding to high concentrations of scatters from large and moist particulates (i.e. cloud drops, drizzle, rain, etc.), and blue for low values of aerosol backscatter. Changes in aerosol backscatter in the vertical denote aerosol layering.

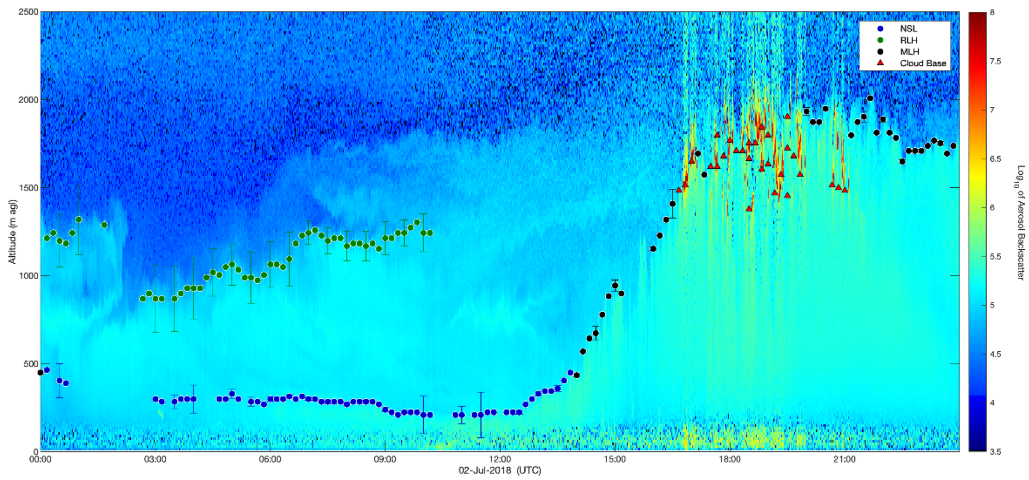

Figure 4. Planetary boundary layer ceilometer aerosol backscatter retrievals. The blue markers represents the height of the NSBL, black markers the ML, and green markers the RL. Red markers denote cloud base.

Figure 4 shows the typical evolution of the PBL during the morning, afternoon, and early evening. Overnight, in the absence of sunlight, the PBL shrinks to a narrow layer next to the Earth's surface, called the Nocturnal Stable Boundary Layer (NSBL, visible from 00:00 UTC until approximately 13:00 UTC in Figure 4). After sunrise, the surface begins to warm, and Mixed Layer (ML) growth begins eventually surpassing the NSBL and reaching the height of the Residual Layer (RL) aloft approximately from ~13:00 to 17:00 UTC in Figure 4. Most of the particulate matter in the PBL is concentrated near the surface, as indicated by the yellow colors in Figure 4.

b. Precipitation

Figure 5 shows the presence of clouds and precipitation in a time series plot of data. The red thin horizontal lines in heights between 1000-7000 meters are due to the presence of clouds. After 5:00 UTC rain is observed and lasting approximately 5.5 hours. The rainfall is discernible from the yellow to red vertical signals extending from the cloud bottom (red horizontal lines) towards the surface. The vertical yellow stripes beginning in higher altitudes and weakens with decreasing height (~12:00 and 22:30 UTC) its signal impacted by increased return signals from solar radiation and by the presence of clouds in the atmosphere.

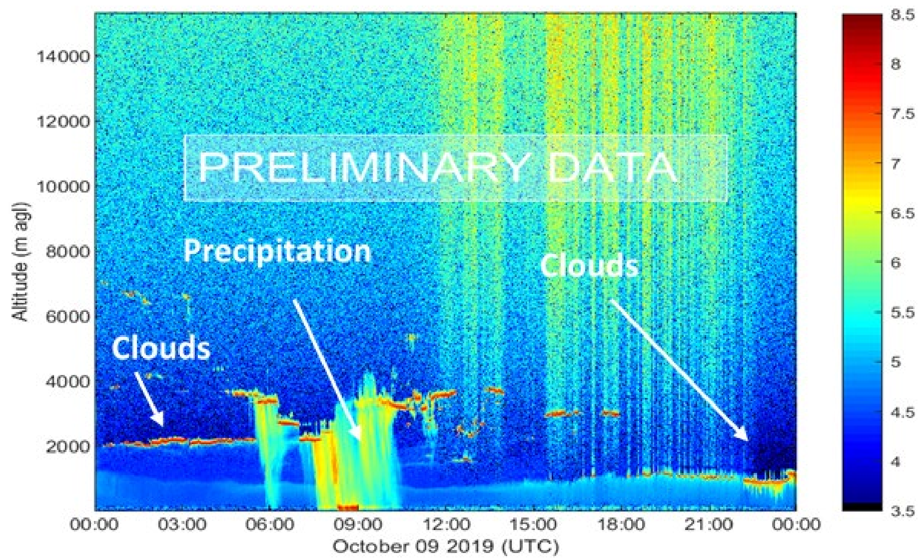

Figure 5. Ceilometer aerosol backscatter retrievals showing the presence of clouds and precipitation.

c. Smoke

A recent smoke transport case was documented using ceilometer sites. From approximately July 8 – July 20, 2019, smoke from Canadian fires was seen in Satellite images over ceilometer sites (Figure 6 left panel). Figure 6 shows aerosol backscatter at two ceilometer sites in New York (top right) and Maryland (bottom right) from July 8, 2019 – July 10, 2019. The aerosol backscatter images show a more complex lower troposphere (0-5000 meters) than the earlier images shown (Figures 4-5). Both aerosol backscatter plots (right panel) begin on July 8, 2019 with the presence of clouds and rain during nighttime through about 16:00 UTC in New York (top right) and 18:00 UTC in Maryland (bottom right). Higher aerosol backscatter within the daytime PBL (~10:00 UTC to 00:00 UTC) is occasionally capped with clouds (red aerosol backscatter intensities) at heights between 1500-2000 meters. Above the PBL (i.e. heights greater than 2500 meters), enhanced aerosol backscatter is observed and indicative of the advection of smoke at both locations. A denser layer aloft can be observed in the New York and Maryland aerosol backscatter profiles and confirmed in the VIIRS “True Color” satellite image (left panel). Ceilometers serve to track aerosol transport and monitoring any impacts above or within the PBL. In the case of Figure 6, the smoke transport was not injected into the PBL and therefore did not affect surface air pollution.

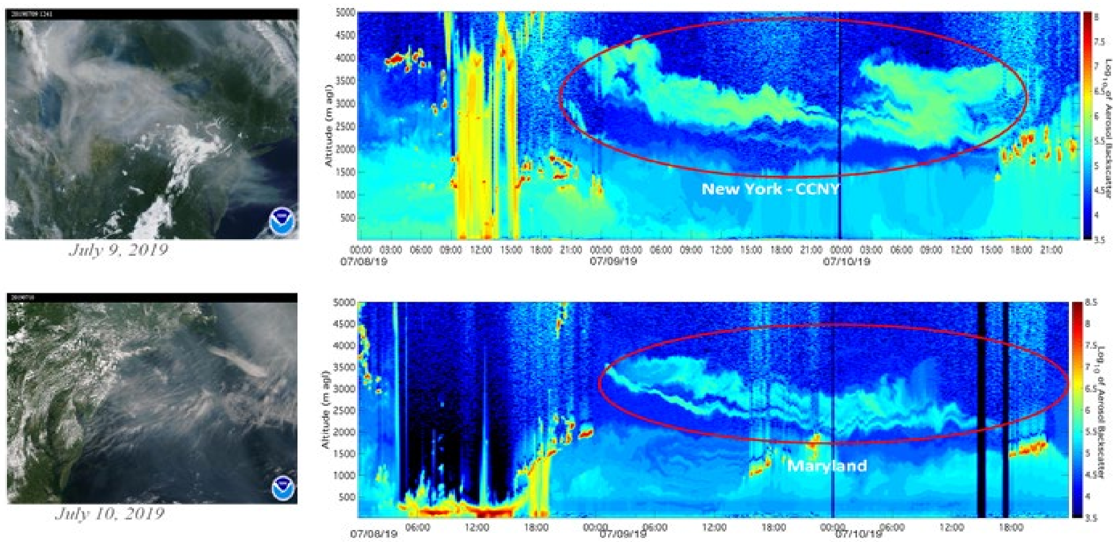

Figure 6. Satellite and aerosol backscatter images for July 8-10, 2020. Satellites “true color” images” from the Visible Infrared Imaging Radiometer Suite (VIIRS) for New York (top left) and Mid-Atlantic states (bottom left), and ceilometer aerosol backscatter time series taken at the City College of New York and Howard University-Beltsville Research Site in Maryland. Satellite images courtesy of NOAA AerosolWatch[16].

d. Instrument Interference

Ceilometer signals and artifacts must be accounted for the correct interpretation of aerosol backscatter measurements and before the application of processing algorithms. For instance, the incomplete lidar signals due to optical overlap can limit ceilometer retrievals in regions below the full overlap greatly impacts near surface ranges (Figure 7a). Adequate corrections for the regions are important for near-surface aerosol layer detection for instruments with increasing range of complete overlap (Figure 7b). Tools such as that described by Hervo et al. (2016) [17] applies a correction function to the known manufacturer’s overlap correction function in order to account for the temperature dependence of the overlap function.

[16] NOAA AerosolWatch: https://www.star.nesdis.noaa.gov/smcd/spb/aq/AerosolWatch/

[17] Hervo et al.; An empirical method to correct for temperature-dependent variations in the overlap function of CHM15k ceilometers, Atmos. Meas. Tech., 9, 2947–2959, 2016.

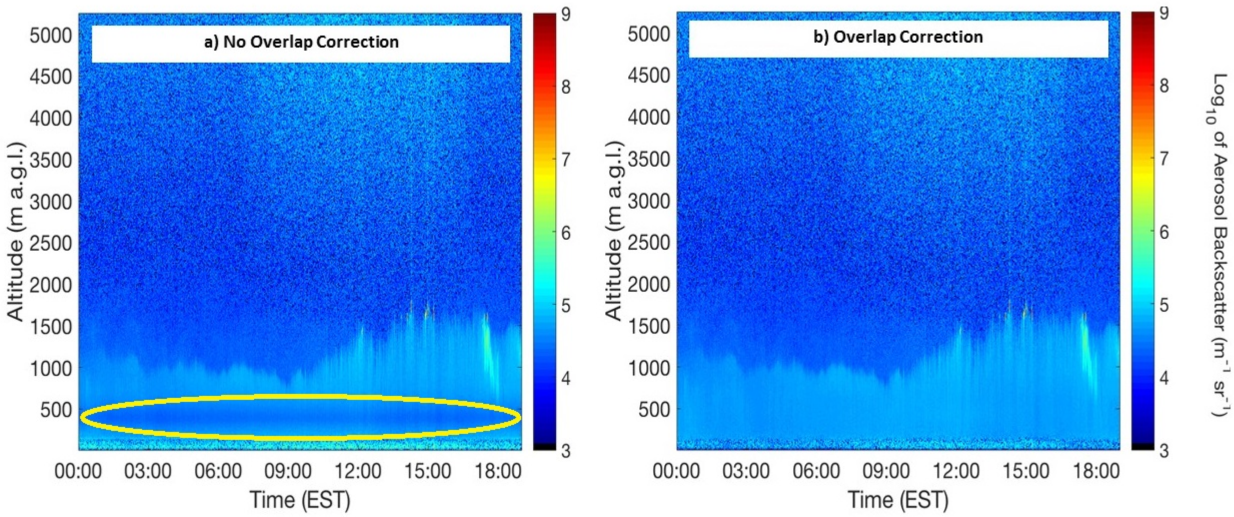

Figure 7. Ceilometer aerosol backscatter time series for signals without an overlap correction (a) and with overlap correction (b).

Some systems display artifacts at specific near-surface gate ranges that need to be accounted for before retrieval methodologies are applied [11,18,19]. Another source of signal interference for ceilometers operating in the 900-910 nm range is the interference from water vapor absorption for which Wiegner et al. (2019)[20] recently proposes corrections. Further, electronic distortion in signals in the upper troposphere and signal artifacts are likely because of environmental temperature on certain system hardware have been found[21]. All these signal interferences must be accounted for before the effective application of the PBL retrieval methodology. The corrections applied to ceilometer signals are used to define the minimum and maximum altitude ranges for PBL height determination.

[18] Sokół et al.; Evaluation of the boundary layer morning transition using the CL-31 ceilometer signals. Acta Geophysica, 62(2), 367–380, 2014.
[19] Kotthaus et al.; Recommendations for processing atmospheric attenuated backscatter profiles from Vaisala CL31 ceilometers, Atmos. Meas. Tech., 9, 3769–3791, 2016.
[20] Wiegner et al.; Aerosol backscatter profiles from ceilometers: validation of water vapor correction in the framework of CeiLinEx2015. Atmos. Meas. Tech. 12, 471–490, 2019.
[21] Madonna et al.; Ceilometer aerosol profiling versus Raman lidar in the frame of the INTERACT campaign of ACTRIS, Atmos. Meas. Tech., 8, 2207–2223, 2015.

6.0 PBL Determination

The diurnal evolution of the PBL typically consists of the convective mixing layer (ML) during the daytime and the residual layer (RL) during nighttime containing the remains of the daytime ML above the near-surface nocturnal stable layer (NSL). These layers are referred to individually as NSL, RL, and ML or collectively as the PBL. To account for the temporal and vertical structure of the PBL, an algorithm is implemented that searches for NSL, RL, and ML signals following the typical daily evolution of the PBL. The automated PBL height retrieval algorithm is described in detail in Caicedo et al. (2020)[13]. The algorithm first addresses aerosol backscatter signal quality and applies corrections and signal smoothing to aerosol backscatter profiles. The algorithm then screens signals for precipitation and clouds, followed by the application of the Haar wavelet transform to aerosol backscatter profiles.

The Haar wavelet method for PBL height retrievals uses the Haar wavelet step function to transform aerosol backscatter profiles highlighting fluctuations in aerosol backscatter profiles. The algorithm uses multiple wavelet dilations to identify aerosol backscatter gradients and retrieve PBL heights[22,23,24]. The covariance transform $w_f(a,b)$ of the Haar wavelet function $h\left(\frac{z-b}{a}\right)$ is defined as

$$w_f(a,b) = a^{-1}\int_{CRS_{min}}^{CRS_{max}} f(z)\, h\left(\frac{z-b}{a}\right)\, dz, \qquad (3)$$

where (*a*) is the dilation factor (vertical extent) of the Haar function, (*b*) is the center of the Haar wavelet function, CRS_{min} and CRS_{max} are the lower and upper ranges of ceilometer, and $f(z)$ is the corrected ceilometer profile ($\overline{CRS}$) as a function of altitude (*z*).

The covariance transform is applied to $\overline{CRS}$ (Fig. 8a) from CRS_{min} to CRS_{max} with incremental dilations (*a*) until the maximum dilation factor is reached (e.g. in Fig. 8b). The determination of the dilation factors or vertical extent of the Haar function (*a*) defines the number of local minimums in $w_f(a,b)$ or the covariance wavelet transform coefficient (CWTC) local minimums. Larger *a* values create fewer large local minimums and lower dilation values create numerous CWTC local minimums at the heights of aerosol gradients in the measured profiles. The algorithm uses the mean of all resulting CWTC profiles ($\overline{CWTC}$)

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[22] Cohn and Angevine; Boundary layer height and entrainment zone thickness measured by lidars and wind-profiling radars, J. Appl. Meteor., 39, 1233–1247, 2000.
[23] Davis et al.; An objective method for deriving atmospheric structure from airborne lidar observations, J. Atmos. Ocean. Tech., 17, 1455–1468, 2000.
[24] Compton et al.; Determination of Planetary Boundary Layer Height on Short Spatial and Temporal Scales: A Demonstration of the Covariance Wavelet Transform in Ground-Based Wind Profiler and Lidar Measurements, J. Atmos. Ocean. Tech., 30, 1566–1575, 2013.

and detects local minimums in the $\overline{CWTC}$ profiles for PBL identification (Fig. 8c). The detection of the CWTC minimum is constrained to the previously defined minimum height for each ceilometer (red bashed line in Figure 8) and to a defined upper height limit (3000m in Figure 8). The PBL height it defined as the local minimum from $\overline{CWTC}$ (black dashed line in Figure 8).

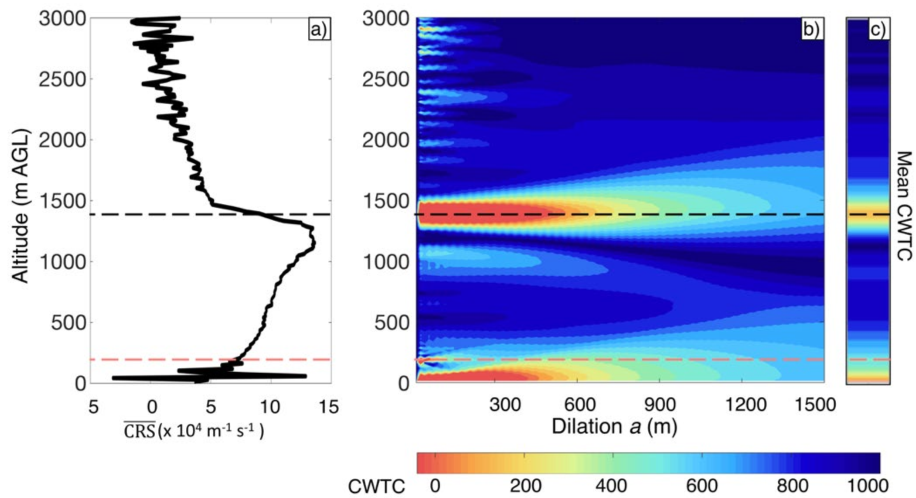

Figure 8. Sample of $\overline{CRS}$ ceilometer profile (a), corresponding CWCT coefficients resulting from covariance transform with increasing dilations 15m to 1500m (b) and resulting mean $\overline{CWTC}$ (c). Red dashed line denotes the minimum reliable altitude range for PBL height detection, and black dashed line indicates the retrieved PBL height. Modified from Caicedo et al. (2020).

Using continuation parameters and calculated uncertainties in PBL height retrievals, the algorithm outputs PBL heights and cloud-base heights. Figure 9 displays algorithm retrieval outputs for four commercial ceilometer models for both cloud base heights and PBL heights. The algorithm has been validated using radiosonde measurements (red markers) in Caicedo et al. (2020)[14].

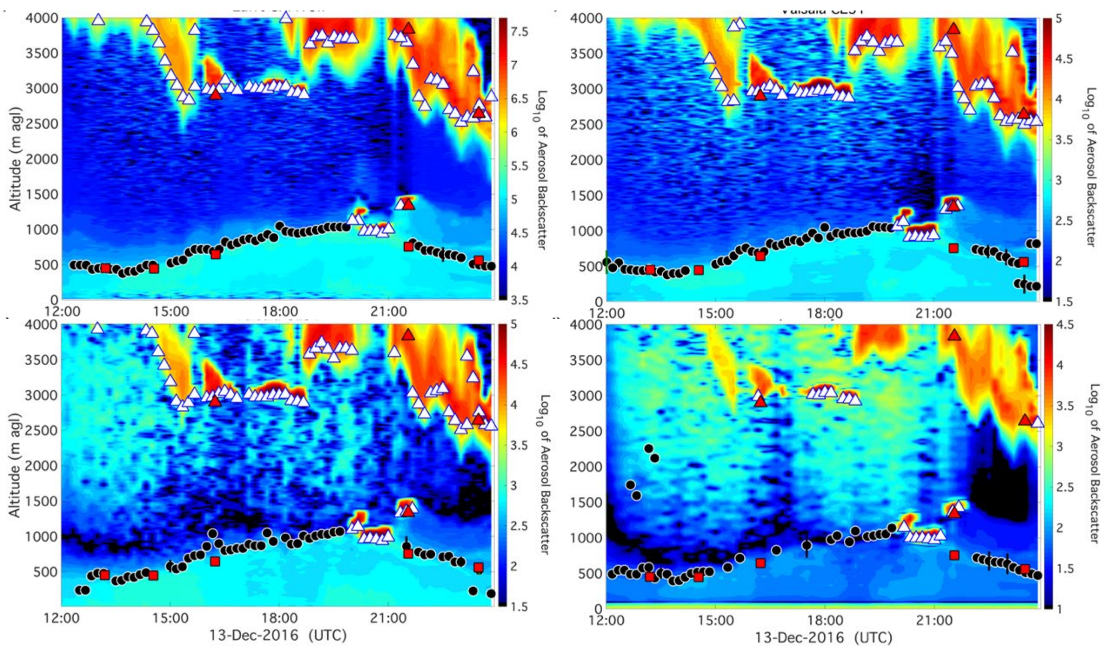

Figure 9. $\overline{CWTC}$ profiles from four commercial ceilometer systems. PBL height retrievals are displayed in black circles, cloud base heights as white triangles. For validation, radiosonde PBL heights (red squares) and cloud base heights (red triangles) are also displayed. Modified from Caicedo et al. (2020)[14].