Simple Off-The-Shelf Ceilometers Find Increasing Applications in Air Quality

In recent decades meteorological sensors based on the scattering of light have moved from specialised research applications to routine operational use. For example roadside weather stations often have forward scatter sensors measuring visibility or identifying weather and most people reading this will have seen them. Similar sensors are widely used at airports and for a variety of other applications. Ceilometers using LIDAR (LIght Detection And Ranging) techniques are now used routinely by meteorologists and at many airports to determine cloud base by measuring the time it takes for light scattered from clouds to return to the sensor. These sensors are becoming increasingly sophisticated and are able to derive a lot more information about the atmosphere than just cloud height. In particular they can derive boundary layer structure of great interest for air quality forecasts more cost-effectively than Doppler LIDAR or other techniques.

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Author/Contact Details:
Mike Brettle
Product Manager, Optical Sensors
Campbell Scientific Ldt.
80 Hathern Road, Shepshed,
Lecis., LE12 9GX
United Kingdom
Email: mike.brettle@campbellsci.co.uk

Basic LIDAR techniques are now widely used to determine cloud base by measuring the time it takes for light scattered from clouds to return to the sensor. In practice this is not as straightforward as it first sounds. Clouds do not have an abrupt, clearly defined base returning a sharp ‘echo’. In practice a ceilometer measures a profile of scattering (in units of sr^{-1}m^{-1}, in effect the proportion of scatter over a unit solid angle over unit distance). It then uses specialised algorithms to identify a cloud base. Typically this is based on a combination of identifying a rate of change of scattering and some criteria based on the calculated horizontal visibility. For the Campbell Scientific CS135 ceilometer (figure 1) this criterion, at lower levels, is a calculated horizontal visibility of 1,000m. This is the visibility criteria for fog so is a familiar threshold for pilots. Interestingly, it might be that the pilot of an aircraft flying in cloud a hundred meters above its base could see the ground below if he looked straight down (an observer on the ground would also see the aircraft as it passed directly overhead) but as regards aircraft around him or obstacles ahead he would be flying well within fog limits.

Figure 1: A modern ceilometer.

Figure 2: Schematic of the optical system of the CS135 ceilometer showing how a lens split by an opaque barrier allows the laser and detector to be close together.

A ceilometer such as the Campbell Scientific CS135 (figure 1) may look simple but contains sophisticated optics and signal processing. The low noise signal processing allows measurements of small backscatter signals from aerosols. The optics in this model are based on a relatively large lens allowing a large collection area. This lens is cut and divided by an opaque barrier to allow the laser emitter and photodiode detector to be very close (figure 2). This is important because it means there will be significant overlap between their fields of view at relatively low levels allowing useful measurements within the lower levels of the atmospheric boundary layer, while still maintaining good optical isolation of the channels.

A ceilometer measures the profile of scattering in the atmosphere and this raises the obvious question as to whether more can be made of this information, especially since it is available from relatively cheap ‘off the shelf’ instruments. Air quality is an obvious candidate application. It is of great importance but some of the key parameters required for forecasting the development of the atmospheric boundary layer are difficult to measure.

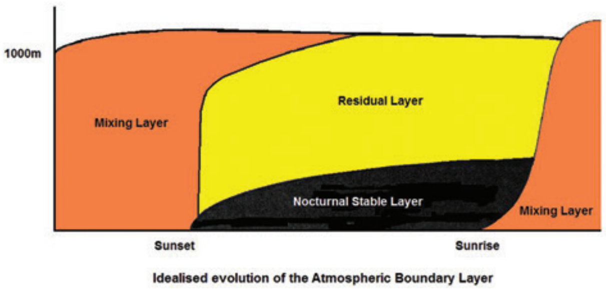

Figure 3: Idealised diurnal evolution of the atmospheric boundary layer.

Figure 3 gives a very simplified model of the typical evolution of the atmospheric boundary layer. Note the growth of the mixing layer during the day and its collapse around sunset. This is, as it’s name implies, the layer through which air, and by implication pollution released at the surface, is mixed.

Mixing layer height (MLH) strongly influences air quality since concentrations at the surface decrease with the depth over which mixing is taking place. In the past various remote sensing instruments have been used to profile the boundary layer. Doppler lidar systems can be used to profile atmospheric boundary layers by measuring the turbulence characteristics in the atmosphere. They do this using the Doppler shift in light scattered by aerosols and cloud particles. In a sense this could be considered a fundamental measurement since it is actually measuring the very parameter relevant to the core issue – the depth over which mixing is occurring. However, they have some limitations, not least cost. Radiosonde soundings can identify the characteristic temperature profile that mark layers within the atmosphere but they are extremely expensive. A ceilometer can be used to identify mixing layers from the backscatter profile from aerosols such as dust and other particulates. However the scattering involved is orders of magnitude smaller than that from cloud particles. This means that the ceilometer has to be designed to have very low noise levels, and long averaging periods (up to 30 minutes) are often needed. The basic physics involved is the same as for cloud detection but instead the algorithms are looking for a fall in backscatter with height. This is the so called 'gradient method'. The processing algorithm looks for peaks in the negative gradient of the scatter coefficient. It is assumed that a sharp drop in backscatter corresponds to the top of the mixing layer.

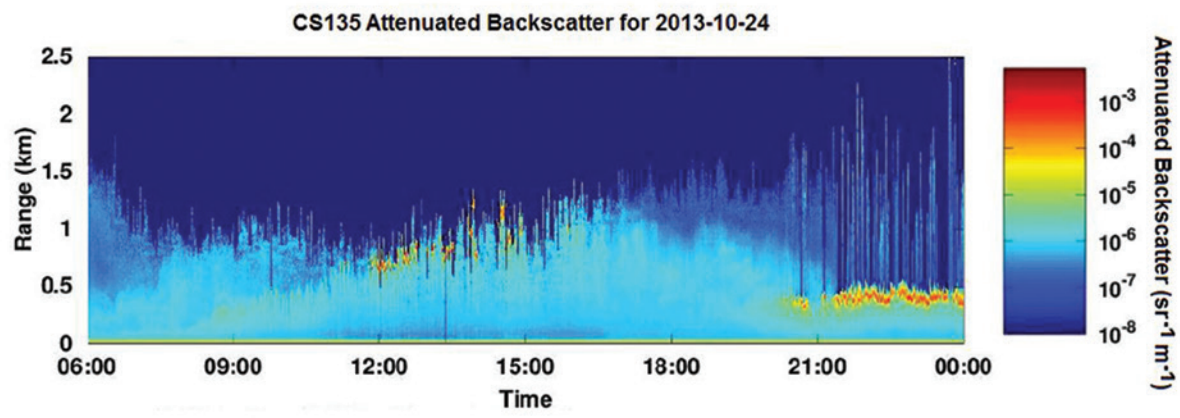

Figure 4: Backscatter measured from a prototype ceilometer. The growth of the mixing layer through the day shows up well as does the stable boundary layer that developed overnight. The higher backscatter, shown by the red colours, marks clouds at the top of this layer.

Figure 4 shows backscatter measured from a prototype ceilometer in Shepshed, UK. The growth of the mixing layer through the day shows up well as does the stable boundary layer that developed overnight. The higher backscatter, shown by the red colours, marks clouds at the top of this layer. Figure 5 gives an example from a production CS135 ceilometer running an algorithm to identify MLH. The left hand plot shows cloud hits (red dots) and MLH values (orange dots). The right hand plot gives actual backscatter coefficients over the same period. Features to note are the backscatter coefficients associated with the cloud being several orders of magnitude larger than those associated with the MLH top (10^{-3} sr^{1}m^{-1} as opposed to 10^{-5} sr^{1}m^{-1}). On this day the clouds themselves probably marked the top of a mixing layer. These examples were produced using a gradient method algorithm based on that developed by KNMI [1].

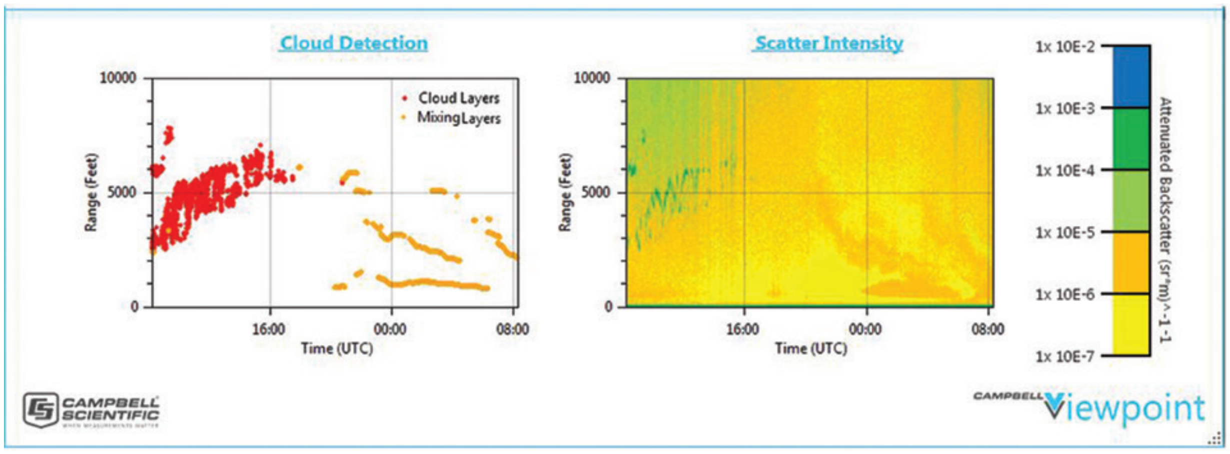

Figure 5: A display of output from a ceilometer running an algorithm to identify MLH. The left hand plot shows cloud hits (red dots) and MLH values (orange dots). The right hand plot gives actual attenuated backscatter coefficients over the same period.

Since the signals measured depend on the type and amount of aerosol present the accuracy of the method varies and therefore a quality factor is assigned which indicates the confidence in the reported layer height. This is based on the ratio of the size of negative peak in the scatter gradient used to identify the MLH to the standard deviation of the scatter gradient. This quality factor is very useful in assessing the importance of a given MLH and in distinguishing between a new growing mixing layer and a residual layer from the previous day.

A ceilometer can produce 'processed' values of MLH as simple numbers in the output message stream, along with associated quality factors, without the need for large data strings containing raw data or specialised software external to the ceilometer to interpret it. This should help these instruments to become widely used.

Sky Condition or Cloud Cover

Modern ceilometers can also measure sky condition. This refers to the amount of sky covered by cloud within a given layer. It is a parameter of particular interest for aviation and also for many applications in synoptic meteorology. It is also very important for meteorological models that derive or use radiation balance for pollution or solar energy studies. This is not a trivial measurement from a ceilometer with a fixed orientation measuring a single point in the sky; the only way to measure sky condition is to rely on the wind to move a representative sample of the sky through the measuring beam. For this reason the algorithms used to identify sky condition have to use a long period of data. Typically cloud height measurements ('hits') from a running 30 minutes are collected but increased weight is given to those in the last 10 minutes. A certain amount of adjustment is required with individual cloud hits being allocated to particular levels. Algorithms used to determine sky condition are mostly 'variations on a theme' with most features being described by, for example, the International Civil Aviation Organisation [2]. However they all have the same strengths and weaknesses when compared to a human observer. The ceilometer will take into account all the changes in the sky over a 30 minute period whereas a human observer will inevitably be biased to the short period he or she is examining the sky. At night of course the human observer will have serious problems. Anyone who has spent time making manual observations at remote sites will be familiar with the frequent 'sudden appearances' of cloud layers at dawn! However, the sky condition algorithm will fail to report stationary or slow moving cloud layers that do not pass through the beam. A good example is the thickening and descending cloud base associated with approaching depressions that may not be picked up until long after a human observer would have picked it up. Conversely if a cloud that only covers a small fraction of the sky is relatively slow moving but stays within the line of sight of the ceilometer then the algorithm will report complete cover. A more subtle difference arises from the way a human looks at the sky, seeing a 'dome' such that he or she is seeing distant clouds from the side. This means that a layer of partial cloud cover made by relatively tall clouds will be exaggerated in extent. A ceilometer taking a sample of the view directly overhead will not have this problem. In theory the difference could be huge. A human observation taken properly according to best practice might report 7/8 of the sky covered by a cloud layer while a ceilometer gives a correct value of 4/8 or less! Comparing human and ceilometer sky condition reports is not trivial.

Stratocumulus Based Calibration of Ceilometers

Calibration of the actual magnitude of the backscatter detected by a ceilometer is increasingly important as the applications become more sophisticated but is not simple. Reliable values for backscatter coefficients are important for air quality and research applications but checking or calibrating an instrument in the field has been, until now, very difficult. The attenuated backscatter can however be calibrated by an automated process based on a method developed at Reading University, UK [3]. The method uses the known scattering properties of a fully-attenuating stratocumulus cloud as a reference. The calibration requires a stable, unbroken, stratocumulus layer with no precipitation present. This is critical as such clouds have reliably known scattering properties. The integrated lidar signal measured is then scaled to match the expected integrated attenuated backscatter. The Campbell Scientific CS135 ceilometer includes a utility to perform this within its operating system. All that is needed is for a human observer to confirm a stable stratocumulus cloud layer at a suitable altitude without holes, precipitation or reduced visibility that has been stable for at least 10 minutes and the ceilometer itself does the rest. A skilled observer still has a role to play despite increasing automation of cloud measurement!

References

[1] Marijn de Haij; Wiel Wauben; Henk Klein Baltink, 2006, Determination of mixing layer height from ceilometer backscatter profile Proc. SPIE6362, Remote Sensing of Clouds and the Atmosphere XI,

[2] ICAO, 2011, Manual on Automatic Meteorological Observing Systems at Aerodromes, ICAO 9837, pp A9 –A13

[3] Ewan J. O'Connor, Anthony J. Illingworth, and Robin J. Hogan, 2004: A Technique for Autocalibration of Cloud Lidar. Journal of Atmospheric and Ocean Technology, 21, pp 777 – 786