The Use of Lidar Technology for Measuring Mixing Heights under the Photochemical Assessment Monitoring Stations (PAMS) Program

Leveraging Research under the Joint DISCOVER-AQ/FRAPPÉ Missions

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This article presents results from the joint DISCOVER-AQ/FRAPPÉ field campaigns conducted over Denver and the Front Range area, where Lidar technology was used to measure mixing heights and compared to atmospheric boundary layer heights determined by radiosondes.

The operational use of ceilometers—a device that uses a laser or other light source to determine distance or height—across the United States has been limited to detection of cloud-base heights across the Automatic Surface Observing Systems (ASOS) primarily operated by the National Weather Service and the Federal Aviation Administration. Continued improvements in the underlying technology over the past decade has resulted in the use of ceilometers to identify aerosol layers throughout the troposphere, including the atmospheric mixing heights.

With the forthcoming requirement to measure hourly mixing heights under the U.S Environmental Protection Agency's (EPA) Photochemical Assessment Monitoring Stations (PAMS) program, ceilometers may provide a cost-effective technological solution. During the joint DISCOVER-AQ/FRAPPÉ field campaigns conducted over Denver and the Front Range area two CL-51 ceilometers were used to measure mixing heights and compared to atmospheric boundary layer heights determined by radiosondes.

The PAMS Program

The PAMS network was established more than 20 years ago to focus on collecting data to characterize causes of ozone exceedances in severe non-attainment areas across the United States. At many of the urban locations with PAMS sites, the nature of the ozone problem has changed over the past two decades. As a result, the PAMS program recently finalized a re-engineering of the network[1] with the new requirements contained in the 2015 National Ambient Air Quality Standard for Ozone.[2]

Starting in 2019, the revised PAMS monitoring requirements mandate hourly mixing height as a required meteorological parameter. Seibert et al. (2000)[3] defined mixing height (MH) as "*the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrained into it become vertically dispersed by convection or mechanical turbulence within a time scale of about an hour*." The spatial and temporal variability of the mixing height over an urban area is a critical parameter in properly modeling pollutant concentrations[4] and developing appropriate air pollution control strategies.[5] However, measuring mixing height at PAMS sites on an operational basis has remained a technological and resource challenge over the span of the program.

As monitoring was implemented under the original PAMS program, most state and local agencies installed radar or sodar wind profilers to measure vertical profiles of horizontal winds, with some agencies adding the Radio Acoustic Sounding System (RASS) extensions for temperature profiling, where the virtual temperature could be used to determine Atmospheric Boundary Layer Height (ABL/ABLH). The ability to systematically archive and process the data from these systems across the PAMS has been sporadic. Over the years, NOAA has worked to incorporate data from some of these systems into their Cooperative Agency Profilers (CAP) Network.

Recently, researchers using measurements collected at Howard University Beltsville Research Campus (HUBRC) in Beltsville, MD, showed a robust method to determine ABLH from the Maryland Department of the Environment RADAR wind profiler.[6] However, RASS temperature profile measurements often do not extend above 1 km, and the wind profilers suffer from poor vertical resolution. Additionally, most of the initial RADAR/RASS profilers are a decade or more old and are in need of either upgrade or replacement.

Measuring Mixing Height over Denver

The Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) Earth Venture Mission[7] focused on the collection of routine and systematic measurements of the vertical distribution of atmospheric trace gases, aerosols, and a variety of physical parameters at the altitudes from the surface through the boundary layer and into the lower troposphere. The Front Range Air Pollution and Photochemistry Éxperiment (FRAPPÉ) focused on photochemistry and emissions characterization. Both field missions conducted in 2014 over the greater Denver and Front Range area provided an opportunity to assess the performance of two Vaisala CL-51

Figure 1: Students from the Millersville University Clarke Atmospheric Research Group preparing to launch a radiosonde at the Golden, CO, research site during the DISCOVER-AQ Earth Venture Mission, August 2014. *Photo by: Richard Clarke, Millersville University.*

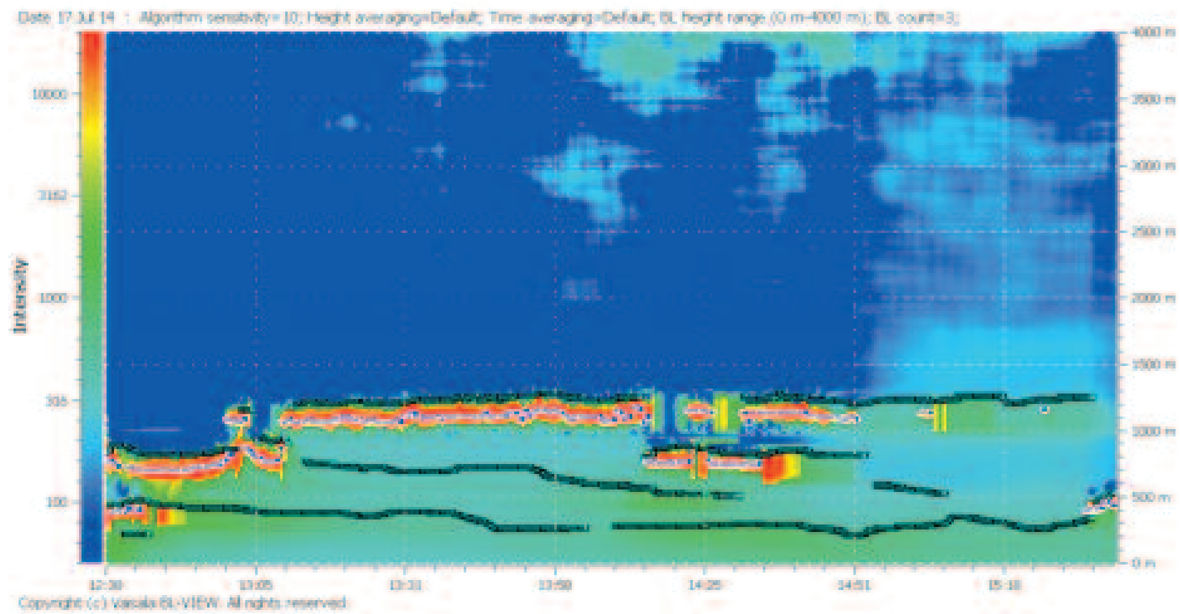

Figure 2: Characteristic backscatter curtain plot generated in BL-View. Data were collected on July, 17, 2014 at the Golden, CO, site during DISCOVER-AQ. The backscatter is plotted from 0 – 4000 m above ground level with a scale for the intensity of the backscatter signal in units of 10^{-9} $m^{-1}sr^{-1}$. The high intensity backscatter (red) is typically an indication of clouds and precipitation. The lighter to medium intensity backscatter (light blue to yellow) is from aerosols. The dark blue represents a "clean" atmosphere. The blue rectangles with a white outline show cloud base heights, and the cyan rectangles with a black outline show aerosol layer heights. In BL-View, the lowest altitude aerosol layer is assumed to represent the mixing height.

ceilometers for continuous measurements of MH through the measurement of attenuated backscatter and variations in the structure of aerosol layers detected through the troposphere.

The most widely accepted method to measure the ABLH involves the use of radiosondes to profile the atmosphere and then use a skew-T plot of the temperature and dew point collected from radiosonde profiles. A radiosonde is a small, expendable instrument package that is suspended below a large balloon inflated with hydrogen or helium gas. As the sonde rises, typical rates of ascent are about 300 meters/minute (about 1,000 feet/minute), sensors on the radiosonde measure profiles of pressure, temperature, and humidity. The data are then transmitted back to a ground receiving station during the weather balloon ascent. Wind speed and direction aloft are also obtained by tracking the position of the radiosonde in flight using GPS or a radio direction finding antenna.

While radiosondes provide excellent vertical resolution of the atmospheric structure for determining ABLH, the temporal resolution is poor because it is not cost effective, due to labor and materials, to launch continuous sondes throughout the day to profile the atmosphere. Conversely, ABLH or MH from remote sensing instruments is often employed to obtain improved temporal resolution and capture the diurnal variations.[8]

During the DISCOVER-AQ and FRAPPÉ campaigns radiosondes were launched from several of the ground-based research sites, including the research sites at Golden, CO, and the NOAA Boulder Atmospheric Observatory (BAO) in Erie, CO. Both the Golden and BOA sites hosted multiple remote sensing profiling instruments, including two CL-51 ceilometers operated by EPA. Figure 1 shows students from Millersville University Atmospheric Research Team launching a radiosonde from the Golden research site on one of the NASA P-3B flight days.

Over the past decade improvements in light detection and ranging (lidar) technology have resulted in greater use of optical remote sensing as a method for MH estimation. The lidar method operates, much like radar, by emitting light into the atmosphere, typically using pulsed lasers. These light pulses are reflected back to a receiver by aerosols, clouds, or different forms of precipitation throughout the atmosphere. The resulting signal strength of each laser pulse return is measured and, based on the time delay between the laser pulse emission and the detection of the backscatter signal, a vertically resolved time-height backscatter profile is generated from the ceilometers.

The Vaisala CL-51 ceilometers deployed at the Golden and BAO sites used lidar with a single-wavelength diode laser (910 nm +/- 10 nm) pulsed at 6.5 kHz (110 ns pulse width). The ceilometers provide 10 m vertical resolution +/- greater

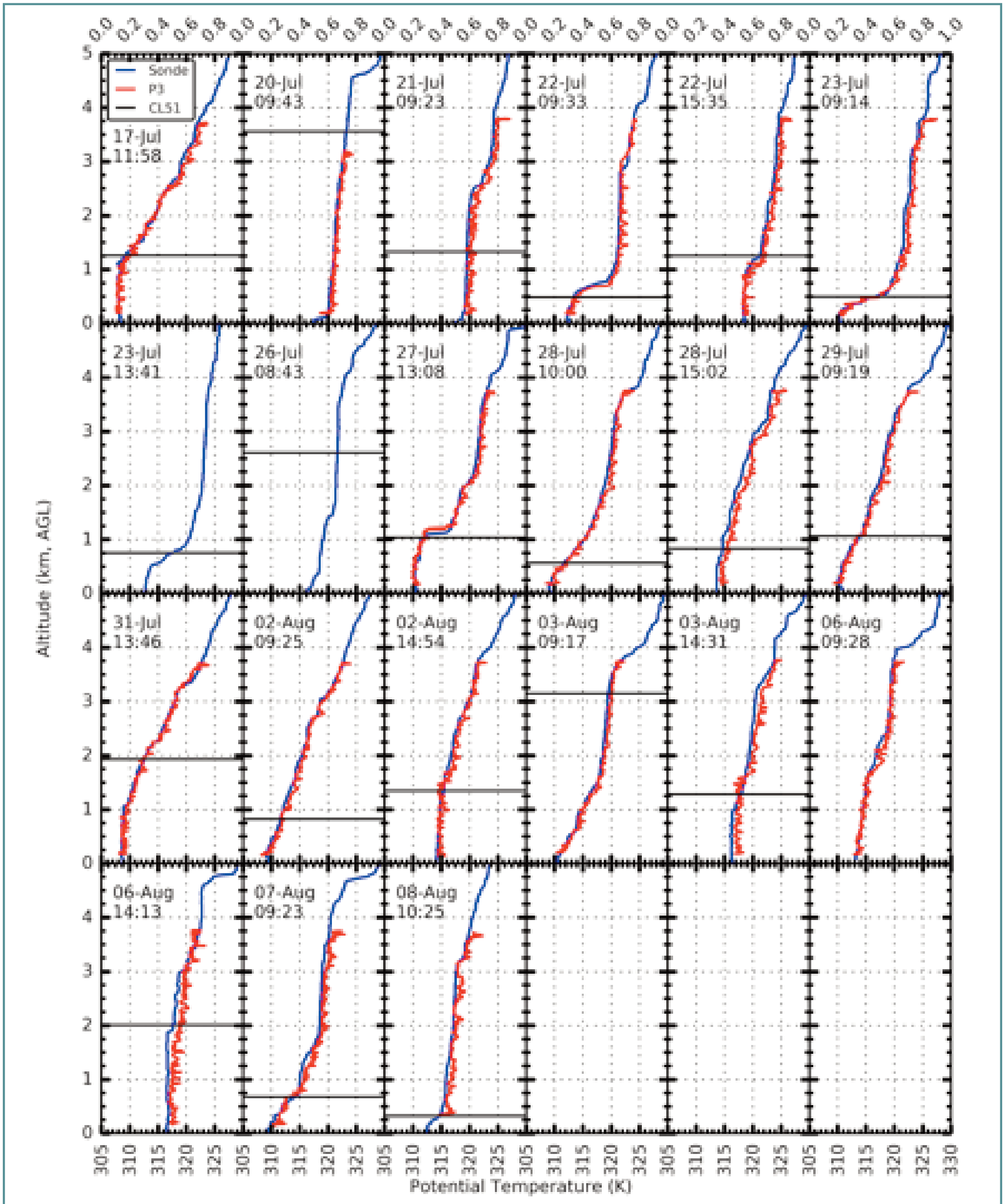

Figure 3: Radiosonde potential temperature and CL-51 ceilometer backscatter profiles collected at the Golden, CO, site. The horizontal lines indicate MH as determined via BL-View.

of 1% or 5 m precision, and a vertical range that extends just past 15 km. Ceilometer profiles can be reported with up to 2 s temporal resolution (depending on the control software), with typical averaging being 16–36 s to improve the signal-to-noise ratio (SNR).[9,10] While it has been shown that ceilometers experience interference from water vapor lines near 910 nm when used for retrieval of aerosol optical properties, the impact of this interference on aerosol profile, aerosol layer detection, and MH estimation is negligible.[11]

For two CL-51 instruments located at Golden and BOA, the MH was estimated using the Vaisala BL-View software. BL-View uses a proprietary algorithm to identify the minimum negative-gradient (*-dβ/dx)* altitude in the backscatter profile. In most cases, the lowest of these gradient minima marks the top of the mixed layer in a well-mixed boundary layer. However, the inherent assumption in using lidar technology (e.g., ceilometers) to estimate MH is that the vertical aerosol distribution adapts rapidly to the changing thermal structure of the boundary layer, and the aerosol remains well mixed within the boundary layer as the ABL increases/decreases throughout the day, allowing the top of the MH to be identified. The BL-View software is capable of identifying up to three aerosol layers based on this approach, so care must be taken when analyzing the data to determine if the lowest layer identified is the actual MH or if residual-layer influences are at play.

The BL-View software also contains the ability to discriminate between MH inversions and changes in backscatter intensity induced by cloud, precipitation, and fog. Figure 2 shows a characteristic backscatter plot generated in BL-View, with MH and cloud heights.

Over the duration of the Denver field campaign, radiosondes were launched from the Golden and BOA sites in close time proximity with the NASA P-3B spirals over each site. Figure 3 shows potential temperature profiles from both the Millersville radiosonde launches during the NASA P-3B spirals over Golden along with the co-incident backscatter measured by the CL-51 during the field campaign. This figure also shows the height of the first major gradient identified by the BL-View software, which is assumed to be the MH. A similar set of plots was generated for the BAO site. Both the Golden and BAO potential temperature profiles from the sondes agreed well with the near co-incident potential temperature profiles from the NASA P-3B over both sites.

Ceilometer Mixing Heights vs. Radiosonde Atmospheric Boundary Layer Heights

The radiosonde-derived ABLH was compared to the CL-51 MH at the BAO-Tower and Golden, CO, sites. A radiosonde captures a snapshot of atmospheric conditions as it ascends, and traverses several kilometers in the horizontal direction due to winds, and hence is a point based measurement in time and space that represents the ABLH of the immediately surrounding area. The CL-51 data represents a temporal and spatial average of the MH due to the averaging of the backscatter measurements. To account for spatial difference between the radiosonde and the CL-51, the ceilometer data were averaged over 30-minutes for comparison. Additionally, each measurement is subject to different potential biases. A radiosonde can be impacted by local updrafts or downdrafts, and result in MH estimates higher or lower than the true MH. The CL-51 MH is sensitive to the backscatter gradient, so if there are additional aerosol layers just above the MH, the contrast between the aerosol layers may not be strong enough for the CL-51 to identify each layer or the correct altitude of the MH. Therefore, resampling the data to reasonable average values (e.g., 30-min means) mitigates the impact of the short-lived perturbations.

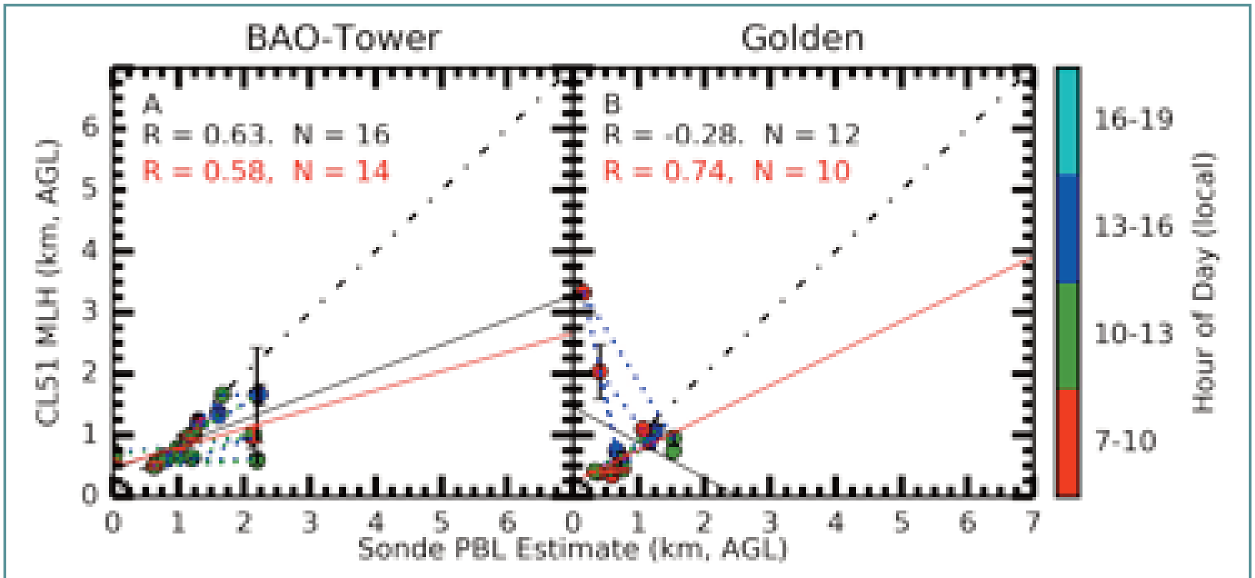

Figure 4: Correlation plots for CL-51 versus radiosonde-derived MH/ABLH estimates for BAO-Tower and Golden, CO. Black text and regression line are for the entire data set, while the red text and regression line represent data with filtering criteria (5-minute σ > 0.20 km or RSD > 20%) applied to the CL-51 data. Data points in each plot are colored to show local time of data.

To determine the ABLH, the temperature, relative humidity, and pressure data collected by each radiosonde was used to calculate potential temperature as a function of altitude, and an objective criteria was applied to identify steep gradients within the potential temperature profile.[12,13] At this point, a fundamental difference between the ceilometer and sonde methodologies is worth noting. The ABLH is based predominantly on the atmosphere's turbulent kinetic energy (i.e., a thermodynamically based condition), while the MH is a product of mixing associated with turbulent kinetic energy (i.e., mixing within the ABL). While this may sound like the same thing, it is not. The ABL is the thermodynamically driven parameter, and MH represents how aerosol responds to this change by either mixing within the ABL or mixing into the ABL. A degree of separation remains between the two.

Figure 4 shows the comparison of the CL-51 MH compared to sonde ABLH for the BOA and Golden sites. There is an apparent discrepancy between Figures 3 and 4 in the number of sonde launches represented in the two. This is due to the lack of an identifiable ABL in the sonde-based profiles for each flight. The initial Golden site correlation was strongly impacted by 2 morning radiosonde launches, which is a transition period when the boundary layer is experiencing rapid growth. Radiosonde ABLH was less than 500 m for these two points, while the CL-51 MH was greater than 2 km, indicative of an aerosol residual layer from the previous day. These two points serve as good examples of how complicated MH estimations can be within the real (i.e., non-ideal) atmosphere.

Upon applying appropriate filtering criteria to the CL-51 MH data where the 5-minute standard deviation (σ) exceeded 200 m or the relative standard deviation (σ/μ) exceeded 20 percent the 2 early morning data points were removed resulting in a much improved correlation. For the BOA site, the initial correlation shows moderate agreement (R=0.63; N=16), with a lower correlation when the filter criteria is applied (R=0.58; N=14). Based on the data from the Golden site it appears to indicate the CL-51 may have difficultly capturing an accurate MH during rapidly changing conditions, such as early morning growth and late evening collapse.

It is somewhat surprising that the filtered correlation for the Golden site is better than the filtered result for the BAO-Tower site, given the BAO-Tower site is situated further to the east of the mountain range, at the start of the High Plains, which is less influenced by very local geographic influences. To check the radiosonde reliability, the radiosonde potential temperature profiles were plotted with profiles collected on the NASA P-3B as it spiraled around the ground site (figure not shown), wherein it is observed that the two profiling methods are in agreement. This adds confidence in the sonde's representation of the surrounding area's ABL since the P-3B spiral was approximately 5 km in radius. The observed differences may be due to the inherent difference between the two profiling methodologies as discussed above.

Conclusion

The results show the CL-51 is capable of capturing hourly mixing height values. Examples were shown, Figure 4B, of how aerosol residual layers influence MH estimation. However, when appropriate screening criteria were applied to the

CL-51 data, the correlations between the CL-51 MH and ABLH estimates from the radiosondes significantly improved for the Golden site, and slightly decreased for the BAO site. On average, the radiosonde ABLH was higher than the CL-51 MH at the BAO (Erie, CO) (390 m (15%)) site, and lower at the Golden (CO) site (-240 m (9%)). A limited number of radiosondes was conducted during nighttime hours, and therefore nighttime MH were not evaluated. Despite differences in the two methodologies, the agreement remains encouraging.

Through an active collaboration among NASA, EPA, NOAA, NCAR, and several Universities during the joint DISCOVER-AQ and FRAPPÉ Missions, the EPA Air, Climate, and Energy Research Program leveraged resources to assess the performance of the CL-51 ceilometer MH with co-incident sonde measurements of ABLH. The in-field evaluation of the CL-51 ceilometers was conducted over a month-long time period in the Denver–Front Range Urban Corridor, at two sites with distinct meteorology, Golden, CO, and BOA Tower in Erie, CO. This demonstration shows the CL-51 ceilometer is a viable solution for satisfying the new PAMS requirement to measure hourly MH. **em**

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