BACKSCATTER NEPHELOMETER TO CALIBRATE SCANNING LIDAR

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ABSTRACT

The general concept of an open-path backscatter nephelometer, its design, principles of calibration and the operational use are discussed. The research-grade instrument, which operates at the wavelength 355 nm, will be co-located with a scanning-lidar at measurement sites near wildfires, and used for the lidar calibration. Such a near-end calibration has significant advantages compared with the conventional method of far-end calibration that assumes an aerosol-free atmosphere at some high altitude.

1. INTRODUCTION

The Kano-Hamilton multiangle method allows extracting the vertical particulate extinction-coefficient profile from the signals of elastic scanning lidar without an a priori selection of the lidar ratio [1, 2]. Assuming a horizontally stratified atmosphere, the angle-dependent lidar equation can be written as

$$\ln\left[P_i(h)(h/\sin\varphi_i)^2\right] = \ln\left[B(h)\right] - 2\tau_t(0,h)/\sin\varphi_i, \quad (1)$$

where $P_i(h)$ is the power of the backscatter signal measured at the height h for elevation angle φ_i ($i = 1\ldots m$); $B(h) = C_{lidar}\beta_t(h)$ is the relative backscatter, here C_{lidar} is a lidar system constant, and $\beta_t(h) = \beta_m(h) + \beta_p(h)$ is the total (molecular and particulate) backscatter coefficient; $\tau_t(0, h) = \tau_m(0, h) + \tau_p(0, h)$ is the total optical depth from ground level to the height h. Using the linear least square fit for the dependence $\ln[P_i(h)(h/\sin\varphi_i)^2]$ versus $(\sin\varphi_i)^{-1}$ for consequent heights, the slope and the intersect of that linear fit can be determined. From these, the profiles of the optical depth, $\tau_t(0, h)$ and the relative backscatter, $B(h)$, are then obtained starting from some minimal height, h_{min}. The particulate optical depth, $\tau_p(0, h)$, found as the difference of $\tau_t(0, h)$ and the molecular component, $\tau_m(0, h)$, is used to compute the vertical particulate extinction coefficient profile, $\kappa_p(h)$. If the constant, C_{lidar}, is someway determined, the particulate backscatter coefficient, $\beta_p(h)$, can be found as.

$$\beta_p = \frac{B(h)}{C_{lidar}} - \beta_m. \quad (2)$$

This in turn, makes it possible to determine the vertical profile of the lidar ratio.

The constant, C_{lidar}, can be determined using the lidar data at a reference height where the particulate component in some way may be estimated. The most common way to do this is through the far-end lidar calibration based on the assumption of an aerosol-free atmosphere at some high altitude. The far-end lidar calibration has two significant drawbacks. First, the selection of the height of the aerosol-free atmosphere based on real knowledge is rarely possible. Commonly, the selection of the height for calibration is based on indirect factors. Second, the lidar signals at the far-end generally have a poor signal-to-noise ratio and a high relative level of systematic distortion, so that an accurate determination of the constant, C_{lidar}, is always an issue. An additional drawback appears when working in smoky-polluted atmospheres near wildfires; in these highly polluted areas, selecting the aerosol-free zone within the lidar measurement range becomes problematic.

The best way to solve this issue would be to replace the far-end lidar calibration, based on the assumption of an aerosol-free atmosphere at high altitudes, with a near-end calibration. Such a near-end calibration could be performed if a direct measurement of the total backscatter at a reference height, for example, close to the lidar-measurement minimal height, h_{min}, were available. In this case, no assumption about the existence and location of aerosol-free atmosphere would be required. However, aside from elevating an instrument at the measurement site, it is not realistic to perform continuous in situ measurements at the required height. The only realistic option is to locate the in situ instrumentation at ground level and compare its readings with the lidar data over minimal heights, close to h_{min}, extrapolated down to ground level. In such a variant, the near-end lidar signals having relatively small systematic distortions and good signal-to-noise ratios are used.

To implement such a near-end calibration, a ground-based fast-response backscatter nephelometer, located at the lidar measurement site, is required. Currently, such instrumentation is not commercially available. In this study, the design of the research-grade backscatter nephelometer, principles of its calibration and operational use for the scanning lidar calibration are considered.

2. GENERAL CONCEPT

A. Analytical description

The general equation for the power of the backscatter signal measured by the backscatter nephelometer is similar to the lidar equation. However, in such a short-path instrument, the backscattered light is collected simultaneously from the whole illuminated volume, starting from some minimal range, r_{min}, which is determined by the minimal distance where the backscattered light is "seen" by the photo detector. Figure 1 shows a schematic representation of the orientation of the photo multiplier tube (PMT) field of view (FOV) and the flash lamp beam. Because the signal intensity decreases proportionally with the inverse squared range, $1/r^2$, the range over which the backscattered light is collected is extremely short. If the complete overlap zone, that is, the range where the flash lamp beam is completely seen by the photo detector starts at $r_{ov} \sim 1$ m, the range where the backscatter power decreases down to 1% will be ~ 10 m. One can consider such a distance (or a little larger) as a maximal

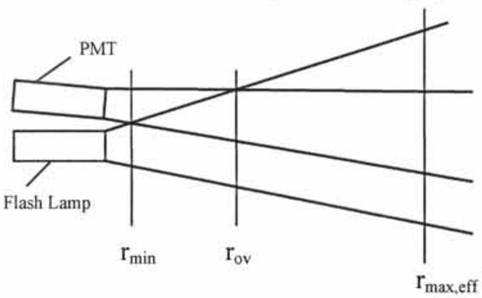

Figure 1. Orientation of the PMT FOV vs. the flash lamp beam in the backscatter nephelometer (not to scale).

effective range, $r_{max,eff}$, ignoring a negligible addition of the backscattering from the distances larger than $r_{max,eff}$.

The total power of the backscattered light collected from the illuminated volume can be written as

$$P_{bsc} = IC_1 \int_{r_{min}}^{r_{max,eff}} \left[\frac{O(r)}{r^2} \beta_t(r) \exp[-2\tau_t(0,r)] \right] dr \qquad (3)$$

where I is the emitted light intensity, C_1 is a constant, which contains all range-independent parameters except I, and $O(r)$ is the overlap function between the light beam and the field of view of the receiver. Because of the short measurement range r_{min} - $r_{max,eff}$, two assumptions can be used when determining the power of the backscattered light with Eq. (3): (1) $\beta_t(r) = \beta_t =$ const., and (2) $\exp[-2\ \tau_t(0,\ r)] \approx 1$. With these assumptions, the input voltage of the receiver can be written as

$$V_{bsc} = IC_1 \beta_t \gamma_{sig} \int_{r_{min}}^{r_{max,eff}} \frac{O(r)}{r^2} dr, \qquad (4)$$

where γ_{sig} is the backscattered light/voltage transformation factor. If a reference signal, V_{ref}, is formed from the same light source and with the same photodetector, the normalized backscatter signal, V^*, determined as the ratio of the two signals, $V^* = V_{bsc}/V_{ref}$, will not depend on intensity of the light source and the factor, γ_{sig}. In our instrument, a separate photodetector with the transformation factor, γ_{ref}, is used for determining the reference signal, that is,

$$V_{ref} = IC_2 \gamma_{ref}. \qquad (5)$$

Accordingly, the normalized backscatter signal, V^*, is determined as

$$V^* = \beta_t C_{neph}, \qquad (6)$$

where the nephelometer constant, C_{neph}, is,

$$C_{neph} = \frac{C_1 \gamma_{sig}}{C_2 \gamma_{ref}} \int_{r_{min}}^{r_{max,eff}} \frac{O(r)}{r^2} dr. \qquad (7)$$

Obviously, any likely changes of the ratio of the transformation factors, $\gamma_{sign}/\gamma_{ref}$ must be taken into in consideration during the instrument operational use.

B. Calibration of the backscatter nephelometer

Before the nephelometer can be used as a reference instrument, its calibration must be performed; this should be done in the condition of a clear atmosphere. From Eq. (6), the nephelometer constant can be found as

$$C_{neph} = V^* / \beta_t. \qquad (8)$$

The total backscatter, β_t, is defined as,

$$\beta_t = \beta_m + \Pi_{\pi,p} \sigma_p, \quad (9)$$

where the molecular backscatter coefficient, β_m, is determined using conventional dependencies between the ambient and standard temperatures and pressure [3]. $\Pi_{\pi,p}$ is the particulate phase function and σ_p is the total particulate scattering coefficient. It is important to mention that for the specific task of the lidar calibration, there is no need to separate the particulate component in β_t from the molecular component. It is enough to measure the total relative backscatter. This significantly relaxes the requirements of measurement accuracy for the backscatter nephelometer. Note also that no information on absorption at ground level is required to determine C_{neph}.

The fractional uncertainty of the nephelometer constant, δC_{neph}, can be defined using the error propagation principles [4] as,

$$\delta C_{neph} = \sqrt{ \begin{aligned} &(\delta V^*)^2 + (\delta\beta_m)^2 (1 - R_\beta)^2 + \\ &+ R_\beta^2 [(\delta\Pi_{\pi,p})^2 + (\delta\sigma_p)^2] \end{aligned} } \qquad (10)$$

where $R_\beta = \beta_p/\beta_t$, and δV^*, $\delta\beta_m$ $\delta\Pi_{\pi,p}$, and $\delta\sigma_p$ are the fractional uncertainties of the corresponding quantities.

As follows from Eqs. (8) and (9), to calibrate the backscatter nephelometer, σ_p and $\Pi_{\pi,p}$ at ground level should be someway estimated. A commercially available nephelometer that measures the particulate scattering coefficient and operates together with the backscatter nephelometer can be used to obtain σ_p. The determination of the particulate phase function, $\Pi_{\pi,p}$, is more difficult; if no related information is available, it should be determined a priori using statistically reasonable values. Typical values of the particulate phase function in clear atmospheres vary over a rather restricted range as compared to variations of the particulate extinction coefficient; this may significantly reduce the uncertainty in the calculated value of β_t in Eq. (9). Also, the backscatter signal measured with the TSI 3563 nephelometer can be used as some sort of a reference for determining β_p. Nevertheless, the calibration uncertainty is larger when the relative level of particulate loading increases. Therefore, the calibration constant of the nephelometer, C_{nehp}, should be determined in clear atmospheres, when the particulate component of the total backscatter, β_p, is much smaller than the molecular component, β_m.

C. Determination of the lidar constant with the backscatter nephelometer located at the lidar measurement site

Before using the backscatter nephelometer to determine the lidar constant, the nephelometer must be checked to ascertain that its constant determined during the last calibration did not change.

As stated above, multiangle lidar measurements allow obtaining the relative backscattering profile, $B(h)$, in Eq. (1) starting from some minimal height, h_{min}. Therefore, the estimation of $B(h)$ at ground level can only be achieved by the extrapolation of the profile, $B(h)$, from some minimal height, h_{min}, to ground. Note, that in multiangle measurements, h_{min} is always significantly less than the lidar incomplete zone, thus, the extrapolation zone is much shorter than for a vertically pointed lidar.

To illustrate the extrapolation, a real profile of $B(h)$ obtained in the vicinity of the I-90 wildfire in Montana on August 12, 2005 is shown in Fig. 2 (the empty diamonds). The linear fit of this profile over the

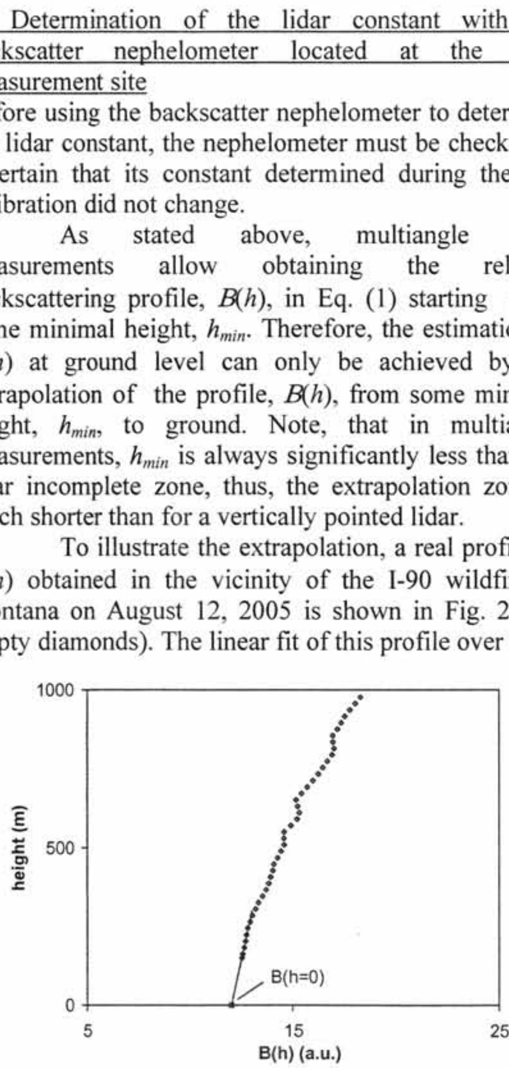

Figure 2. Determination of $B(h)$ on ground level by the extrapolation of the lidar data.

minimal heights (150 m – 270 m) is found and extrapolated to ground level (the thin solid line). The extrapolation down to ground level yields the relative backscatter coefficient at the ground surface, $B(h = 0)$ = 11.8 a.u., shown as the filled square. The lidar constant can now be found using the known lidar constant, C_{neph}, and corresponding nephelometer reading, V^*, as

$$C_{lidar} = C_{neph} \frac{B(h=0)}{V^*}. \qquad (11)$$

3. INSTRUMENT DESCRIPTION

The backscatter instrument can be broken into three sections, transmitter, receiver and control. Figure 3 shows a schematic of the instrument.

The transmitter section consists of a flash lamp and its power supply, and a flash intensity monitor. The flash lamp has an input energy of 230mJ per flash and has an output that is rich in ultraviolet light. Faraday shielding is used throughout the instrument to minimize flash lamp transients. The flash lamp utilizes an integral parabolic reflector producing a beam width of 22 deg. at the 10% relative irradiance level. The life expectancy of the flash lamp is expected to exceed 1 billion flashes. The flash intensity monitor uses a beam splitter to reflect 5% of the flash beam to a photodiode preceded by an interference filter with a center wavelength of 355 nm and a full width at half maximum of 10 nm. A peak detector converts the photodiode output pulse to a DC voltage that is proportional to the peak level; this voltage is automatically held until cleared by the controller.

The receiver section consists of a PMT, the PMT high voltage supply, and signal conditioning electronics. The PMT is preceded by a collimating lens and a 355 nm filter; the filter is identical to that used in the transmitter. The axis of the flash lamp and PMT are located in the same horizontal plane but the axis of the PMT is tilted 5 deg. towards the flash lamp, providing an overlap between the axis of the FOV of the PMT and the flash lamp beam approximately 1 m from the instrument. The full width FOV of the PMT is approximately 9 deg. The PMT output is primarily a voltage proportional to ambient 355 nm light detected, the backscattered light from the flash lamp beam and a background component; PMT noise is small and not considered an issue here. During daylight operation, solar scattering in the atmosphere produces significant background light at 355 nm, which causes a DC voltage shift in the output of the PMT. To eliminate the background voltage, the PMT is capacitively coupled to the signal conditioning circuitry. The PMT output is quite load sensitive and requires special attention in order to maintain device linearity. During daytime operation, a compromise exists with PMT gain such that

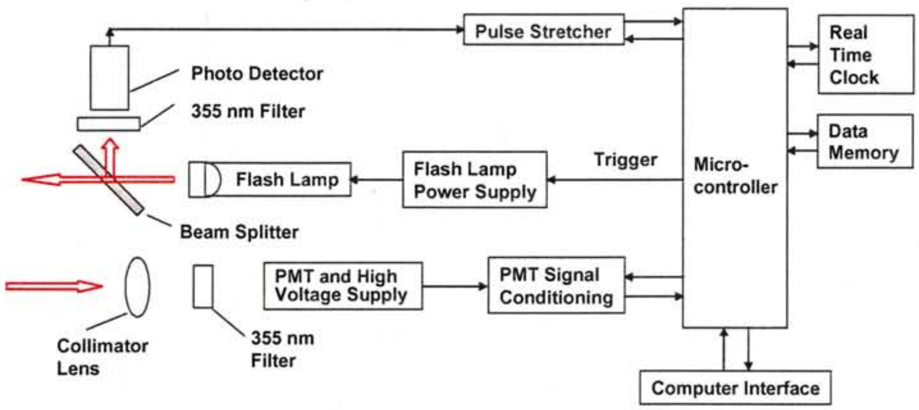

Figure 3. Schematic of backscatter instrument.

the backscatter signal is maximized to a point where the signal due to ambient light does not drive the PMT into non-linear operation.

The PMT signal conditioning circuit consists of a high speed, chopper stabilized, buffer amplifier, an integrator, and a sample and hold circuit. The chopper amplifier buffers the PMT output from the integrator input with minimum offset and drift. The PMT output pulse is integrated to provide high sensitivity while providing a measure of noise immunity when compared to a peak detection circuit. The output of the integrator is held at its final voltage level until an A/D converter can convert it.

Central to the control section is a microcontroller that manages timing, signal conversion, data logging and communication with peripheral devices through an RS232 port. The microcontroller operates at a 20 MHz clock rate, has multiple configurable digital input/output lines, integrated I^2C capability, an integrated Universal Synchronous Asynchronous Receiver/Transmitter, three timer/counters and six, 10 bit A/D converter channels.

The controller runs through two nearly identical sequences when determining backscatter, the only difference between the two is that during the first sequence the flash lamp is not triggered; this provides an opportunity to record any zero input offsets in the transmitter and receiver sections of the instrument. The second sequence is as follows. The peak detector and integrator hold circuits are first cleared. The flash lamp is next triggered and after a short time delay (to allow the flash lamp transients to die away), integration is initiated. At the end of the integration period, the microcontroller triggers the integrator hold. The integrator and peak detector outputs are finally converted by the microcontroller A/D converters; the signals are time stamped, saved to onboard non-volatile memory and output at the RS232 port.

4. SUMMARY

A new research-grade instrument, an open-path backscatter nephelometer, which operates at the wavelength 355 nm, has been developed and preliminarily tested. The instrument is assumed to be located at the scanning-lidar measurement site when working close to wildfires. The backscatter nephelometer will allow determining the lidar solution constant in the smoke-polluted atmospheres where the use of the far-end calibration based on the assumption of the aerosol-free atmosphere is not applicable. During future work, the lidar constants determined through the near-end and far-end calibrations, that is, when using the data of the backscatter nephelometer and the assumption of an aerosol-free zone, respectively, will be compared. In addition, the PMT angle, FOV, and flash beam width will be modified and the effect of these modifications on instrument performance investigated.

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