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Active probing of cloud multiple scattering, optical depth, vertical thickness, and liquid water content using wide-angle imaging lidar

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ABSTRACT

At most optical wavelengths, laser light in a cloud lidar experiment is not absorbed but merely scattered out of the beam, eventually escaping the cloud via multiple scattering. There is much information available in this light scattered far from the input beam, information ignored by traditional "on-beam" lidar. Monitoring these off-beam returns in a fully space- and time-resolved manner is the essence of our unique instrument, Wide Angle Imaging Lidar (WAIL). In effect, WAIL produces wide-field (60-degree full-angle) "movies" of the scattering process and records the cloud's radiative Green functions. A direct data product of WAIL is the distribution of photon path lengths resulting from multiple scattering in the cloud. Following insights from diffusion theory, we can use the measured Green functions to infer the physical thickness and optical depth of the cloud layer, and, from there, estimate the volume-averaged liquid water content. WAIL is notable in that it is applicable to optically thick clouds, a regime in which traditional lidar is reduced to ceilometry. Here we present recent WAIL data on various clouds and discuss the extension of WAIL to full diurnal monitoring by means of an ultra-narrow magneto-optic atomic line filter for daytime measurements.

1. INTRODUCTION

In the quest to quantify the phenomena driving the earth's climate, clouds are perhaps the most important and least understood component of the atmosphere. Passive remote sensing can provide considerable information on clouds, but a more detailed understanding demands active probing. But for remote sensing of cloud properties, traditional "on-beam" lidar, which collects returns from only a very narrow field of view centered on the transmitted laser beam, yields only a small fraction of the information potentially available. For the optically thick clouds typical of the boundary layer, conventional lidar is typically limited to providing the range to the first interface (i.e., cloud base from the ground, cloud top from airborne platforms.) This limitation is largely an artificial one, however. The key to the work described here is the recognition that, at most visible and near-IR wavelengths, lidar photons are not absorbed but merely scattered out of the beam. Much additional information exists in these multiply-scattered photons exiting the cloud far from the input beam. Such photons have typically undergone many scattering events, and have thoroughly sampled the cloud's internal structure before they eventually reemerge, sometimes as much as a kilometer from the input beam. Here we describe a new instrument, Wide-Angle Imaging Lidar (WAIL) which aims specifically at measuring these large-displacement returns. With a field of view of approximately 1 radian, our ground-based instrument provides time-resolved 2D imaging of the returning light, or in essence, "movies" of the light propagation. Mathematically speaking, by measuring the complete spatial and temporal profiles of the returning light, WAIL in effect measures the Green functions (GFs), or radiative impulse response functions, of the cloud, since a pulsed laser is essentially a Dirac δ -function in space and time. The temporal Green function, essentially the time dependence of the spatially-integrated return, is directly related to the distribution of photon pathlengths and is of interest in itself.

A key insight, allowing cloud properties to be extracted from WAIL data, was obtained by Davis et al.^{1,2} the extent of the temporal Green function (i.e., its decay time) is dominated by the physical thickness of the cloud, while the lateral extent of spatial Green function (i.e., its root-mean-square diameter), is influenced strongly by cloud optical depth. Thus both the thickness of the cloud and its optical density can be inferred from off-beam lidar. These two cloud properties

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are of direct interest in a variety of meteorological applications, most notably to clarify the effect of clouds on atmospheric radiative transfer and energy deposition for climate modeling. In addition, once the cloud thickness and optical density are determined, one can infer the liquid water content (LWC), in a volume-averaged manner, via the mean extinction coefficient (i.e., optical depth divided by cloud thickness) together with an educated guess at the effective drop radius. This represents a significant increase in information obtainable from lidar.

We report here on the status of the emerging technology in WAIL, as implemented for ground-based observations, and the associated retrieval schemes.

2. WIDE-ANGLE IMAGING LIDAR (WAIL) INSTRUMENTATION

The basic idea of WAIL is to send a short-pulse, narrow-beam laser into a cloud, and record, as a function of both space and time, the intensity of the returning light over a wide field of view. In essence, one wants to take a "movie" of the propagation of the multiply-scattered light.^{2,3} The first realization of such a fully imaging WAIL instrument relies on unique imaging detector technology developed at Los Alamos National Laboratory, the Micro-channel Plate/Crossed Delay Line (MCP/CDL) detector, coupled with high-speed pulse absolute timing electronics.⁴ The MCP/CDL technology features photon-counting sensitivity, a large spatial format (4 cm diameter active area, effectively up to $\approx 1500^2$ pixels), and ultra-high time resolution (100 ps). It consists of the MCP/CDL detector — a photo-cathode coated vacuum tube, intensified by micro-channel plates, read out by a crossed delay line anode — together with fast pulse-timing electronics. Each photo-electron is intensified by a factor of 10^7 , with positional information preserved, by the MCP. The electron cloud is collected by helically wound delay lines, producing in each line two counter-propagating current pulses which emerge from the ends. By measuring the arrival times of the pulses at the ends of the delay lines, the position of the original photon event is determined; with two orthogonal delay lines, both the x - and y - coordinates are determined.

This unique strategy for extracting spatial information distinguishes the MCP/CDL from other sensitive imagers such as gated/intensified CCDs in that it is intrinsically very fast, with photon arrival time automatically known to within 100 ps as a by-product of the imaging scheme. As an early test, we exploited this extremely high time resolution (100 ps corresponds to a pathlength of only 3 cm) to perform laboratory-scale simulations of off-beam lidar, where the "cloud" was a sizeable aquarium filled with a scattering liquid suspension.⁵ One final thing to note about the idiosyncrasies of this detector is that it is not only capable of performing at very low light-levels, but actually requires them: too high a count rate ($> 5 \times 10^6$ /sec over the entire detector) confuses the timing-based imaging scheme.

These strengths and limitations drive the choice of laser for the imaging lidar system. The count rate limit demands a high repetition rate and averaging over many pulses. A repetition rate around 5–15 kHz is ideal, permitting maximal pulse averaging while avoiding the return from one pulse overlapping with the next. The MCP's spectral response makes a 532 nm frequency-doubled Nd:YAG laser a good choice. Our laser produces 0.2 to 0.5 mJ/pulse, at a variable rep rate (12 kHz is typical in our experiments), with pulse widths ranging from 30 ns to 50 ns depending on operating conditions. The laser is triggered by a master clock, which also provides the timing reference for the detector system electronics.

This nighttime WAIL implementation uses a standard medium-format camera lens with a 35 mm focal length to feed the detector, thus obtaining a full-angle FOV of 60°. This wide angle is needed for ground-based measurements, because the high-order scattering tail of interest here extends up to a kilometer from the beam, a distance comparable to the typical range to the cloud base. One challenge in designing an imaging lidar system for clouds is the large dynamic range, several orders of magnitude, between the initial return (the traditional on-beam lidar signal) and the multiply scattered returns from locations at very large displacements from the beam. The faint large-displacement returns require a band-pass filter, ≈ 10 nm wide for nighttime work, to reject as much background light as possible.

The use of interference filters presents an apparent problem, given the wide field of view, since, as is well known, the band center for standard interference filters varies strongly with angle of incidence. Over the 30° half-angle range of our system, the passband center wavelength shifts nearly 15 nm to shorter wavelengths as one moves from the center to the

edge of the field. This angular sensitivity, however, can be put to use to partially cancel the strong center-to-edge gradient intrinsic to cloud returns but challenging to any detector system, particularly to our MCP/CDL. If, instead of a filter centered (at normal incidence) at the laser wavelength, one chooses a somewhat longer nominal filter wavelength, light at large angles of incidence (i.e., coming from the edge of the FOV) will be near the angle-shifted center of the filter passband, while light near normal incidence (i.e., coming from the bright central spot) will be in the wings of the filter passband and be strongly attenuated. The resulting images in this case will show a bright annular region of strong transmission with a dark center.

Our second implementation of the WAIL concept, recently deployed in an experiment at the DOE Atmospheric Radiation Measurements (ARM) program Cloud and Radiation Testbed (CART) site in Oklahoma, makes use of a commercial (Roper Scientific/Princeton Instruments "PI-Max") intensified gated CCD as the receiver. For this 18 mm detector array, we use a 12.5 mm f.l. lens, resulting in a 70-degree square field of view. To keep data volumes manageable, we bin the original 512x512 pixel images down to 128x128 pixels.

The gated/intensified CCD detector technology, like the MCP/CDL, uses a micro-channel plate photomultiplier, but there the similarity ends. First, the MCP/CDL has an ultimate time resolution of 100 ps, compared to 2 ns for the CCD system, but this difference is unimportant for cloud measurements where relevant time scales are tens of ns and longer. More important are the differences in the basic modes of operation. Unlike the MCP/CDL system, which time-tags each

Figure 1: Nighttime WAIL results using the MCP/CDL detector system. Shown here are the spatially integrated total return as a function of time (graphs) and a sequence of selected frames from the corresponding WAIL "movies" which show the spatial distribution of the returning light as a function of time. The full-angle FOV is approximately 60 degrees. Two data sets for essentially the same cloud deck are shown, being taken a few minutes apart. These were obtained with two different filters on the optics, one that emphasizes the large-angle returns (top) and the other emphasizing the center region (bottom). Narrow bandpass interference filters are generally used to reject background light, but also affect the spatial response of the system (see text for details). Each sequence begins with the Rayleigh/aerosol-scattered beam as it leaves the laser (located off the bottom right side of the FOV); a shadowband blocks the brightest portion of this early return. For these early times, the system is effectively bistatic. Subsequent frames show the aerosol-scattered pulse several hundred meters up, the initial impact on the cloud deck, and subsequent spreading due to multiple scattering.

photon as it arrives, producing raw data consisting of a long stream of time- and space-tagged photon events, the gated CCD system achieves time resolution by electronically gating the intensifier, with gate delay and gate width as adjustable parameters. The MCP/CDL system collects an entire time series for each laser pulse (although only a few photons per pulse can be collected), with good statistics achieved by integrating results for many pulses. The intensified gated CCD, in contrast, collects returns for a single delay time (determined by the gate delay setting), again integrating multiple pulses to achieve good statistics, then advances the gate delay relative to the laser trigger to collect the next "movie frame." There are advantages and disadvantages to both approaches. The CCD can collect many more photons per laser pulse than the MCP/CDL system, the latter being severely constrained by its pulse-timing imaging scheme. Also, the programmable, adjustable gate width of the CCD system allows the exposure time to be adjusted automatically during the course of the measurement, with short exposures for the bright early returns, and longer exposures for the dim high-order scattering. This considerably ameliorates the problems caused by the large dynamic range of the cloud-scattered returns. On the other hand, both systems require total integration times on the order of a minute to collect a complete scattering "movie" with good statistics, and clouds can change on this time scale. The MCP/CDL has the advantage of collecting complete time sequences for each shot, with the result that a time-varying cloud is simply averaged in a straightforward manner in the final multi-pulse integrated data set. But if the cloud changes significantly during measurement with the CCD system, the beginning and end of the time sequence may correspond to very different clouds. Thus with a rapidly varying cloud deck, it is necessary to average many CCD data sets to achieve well-averaged data comparable to that obtained with the MCP/CDL version.

Figure 2: Nighttime WAIL results from the Oklahoma CART site, March 24, 2002, using the gated intensified CCD detector system. Top row shows representative WAIL time slices, showing cloud impact and subsequent spreading, using the 536 nm band center interference filter, which passes the center region while suppressing the large angle scattering. Bottom row shows corresponding frames from a data set using the 546 nm filter, which passes returns from the edge of the f.o.v. Field of view of each frame is 70 degrees. CCD gate width is 50 ns.

Figures 1 and 2 show representative results from the two detector systems. Figure 1 shows nighttime results for a multi-layer cloud deck, probed with two different filters on the MCP/CDL detector, one (nominal band center at 540 nm) which strongly suppresses the center spot, and the other (nominal band center at 536 nm) providing a more uniform response across the field. In each case, the spatially integrated return as a function of time (i.e. the temporal Green function) is plotted, along with representative frames of the spatial WAIL "movie," each frame showing the full 60° FOV. Figure 2 shows sample frames from CCD data sets collected at DOE's Southern Great Plains Cloud and Radiation Testbed (CART) site, again with two interference filters, this time 536 nm and 546 nm.

In both cases, we see cloud-base impacts followed by a strong spreading due to multiple scattering in the highest/densest layer. For QuickTime™ movie versions of these and other datasets, see <http://nis-www.lanl.gov/~love/clouds.html>.

3. RETRIEVAL OF CLOUD PROPERTIES USING WAIL DATA

In previous papers^{1-3,5-9} we have presented detailed theoretical treatments of off-beam lidar in the diffusion regime, both analytical and numerical Monte Carlo modeling. Here we present a brief summary of the key results relevant to interpreting WAIL data.

The schematic in Fig. 3 shows the geometry of off-beam cloud lidar observations. The key quantities are cloud optical depth (τ), physical thickness (H), asymmetry factor of scattering phase function (g), and range (d_{obs}). We are interested exclusively in the remotely observable radiative transfer $GF_{(\text{obs})}$, that is, for escaping radiation, excited by a δ -function source at the cloud boundary. It will depend parametrically on all of the above cloud quantities as well as two independent variables for space and one for time. The spatial variables can be expressed as cylindrical coordinates (ρ, ϕ),

Figure 3: Geometry of off-beam cloud lidar. Shown from left to right, are illustrated meanings for: (1) cloud optical depth τ , physical thickness H , their ratio (extinction σ), and asymmetry factor g (mean cosine of scattering angle ≈ 0.85 for typical droplet populations); (2) space (radius and angle) and time variables. Schematic scatter paths are shown for a ground-based WAIL system and, at right, for an airborne or satellite observation.

with the laser beam defining the axis. The temporal variable can be either time elapsed since the pulse impacted the cloud (t), or the “in-cloud” pathlength ($\lambda = ct$), noting that the “out-of-cloud” portion of total pathlength is simply $d_{\text{obs}}(1 + 1/\cos\theta_p)$.

The results of the analytic theory of greatest interest here are given in equations (1) and (3) below. These results are (a) that the mean pathlength of the returning lidar photons, $\langle\lambda\rangle_R$, is (apart from a small correction) proportional to the cloud physical thickness H , and (b) that the mean-square radius of the diffuse spot, $\langle\rho^2\rangle_R$, is (again, apart from a small correction) proportional to the cloud thickness squared divided by the optical depth, τ . The subscript R indicates that these equations are derived for the reflection geometry; corresponding equations can be derived for transmission measurements.

$$\langle\lambda\rangle_R = 2\chi H [1 + C_{R\lambda}(1, \epsilon)] \quad (1)$$

for mean pathlength, and

$$\langle\lambda^2\rangle_R = \frac{4\chi}{5} H^2 (1-g)\tau [1 + C_{R\lambda}(2, \epsilon)] \quad (2)$$

for the 2nd moment of pathlength, and

$$\langle \rho^2 \rangle_R = \frac{8\chi}{3} \frac{H^2}{(1-g)\tau} [1 + C_{R\rho}(2,\epsilon)] \quad (3)$$

for the variance in horizontal transport. The radiative quantities in (1–3) contain pre-asymptotic correction terms given by:

$$C_{R\lambda}(1,\epsilon) = C_{R\rho}(2,\epsilon) = (\epsilon/2)(1+3\epsilon/2)/(1+\epsilon), \quad (4a)$$

$$C_{R\lambda}(2,\epsilon) = (\epsilon/2)(8+41\epsilon/2+75\epsilon^2/4+\epsilon^3/8)/(1+\epsilon)^2. \quad (4b)$$

These corrections become small as

$$\epsilon = 2\chi/(1-g)\tau = 2\chi\lambda_l/H = T/R \quad (5)$$

decreases (τ increases).

By combining the temporal and spatial information from off-beam lidar —the mean pathlength from the temporal Green function, Eq. (1), and the mean-square horizontal displacement from the spatial Green function, Eq. (3)— both the cloud thickness H and optical depth τ can be determined. A time-only retrieval of H and τ can, in principle, be obtained using the first two moments of the temporal Green function. The time-only retrieval, however, is subject to much greater uncertainties than the full space-time retrieval.

In Fig. 4 we apply this analysis, together with predictions from the corresponding Monte Carlo simulations, to extract cloud properties from the WAIL data shown in Fig. 1. Two methods for extracting physical cloud thickness H and optical depth τ are shown, one in which we make use of both the spatial and temporal information contained in the WAIL data (the most accurate method), and a second method which uses only the temporal information. This latter, time-only analysis is useful in that it can be applied to simpler non-imaging off-beam lidar systems. Reassuringly, the cloud parameters obtained from the two methods are consistent with each other and appear reasonable for the altostratus layer that was visually observed during the measurement. But to achieve this congruence of the two methods it was necessary to account for the internal stratification of the cloud layer seen in Fig. 1.

For both methods, the lower curve is used to determine the optical depth τ . However, for the time-only scheme in Fig. 4a we immediately notice the large range of possible values for τ based on the experimental value of $\langle \lambda^2 \rangle_R^{1/2}/\langle \lambda \rangle_R$: τ can be anywhere from 2 to 10 (even 1 to 20 or broader, given some measurement error). The cloud height information in Fig. 1 (this is an altostratus) argues for the lower end of the range in τ but we proceed without using this. From the upper curve, the cloud thickness can be determined, given the mean pathlength $\langle \lambda \rangle_R \approx 1.37$ km. The inferred value of H is, fortunately, not very sensitive to τ and we find H between 0.48 (possibly a little less, given some measurement error) to 0.56 km. This is reasonable for the nocturnal altostratus layer present in Fig. 1.

The combined space and time method in Fig. 4b yields similar, but much less uncertain results. Starting with the experimentally measured value of $\langle \rho^2 \rangle_R^{1/2}/\langle \lambda \rangle_R$ of 0.76, one infers from the curves a value for τ of about 3, with little uncertainty. This value is quite reasonable for altostratus. The associated value of the thickness H is in the middle of the range obtained from the time-only scheme, around 0.52 km. The time-only and space-time methods thus yield comparable results.

Figure 4: Retrieval of cloud properties from the WAIL data in Fig. 1. (a) Time-only scheme. (b) Combined space-time scheme. The lower curves show calculated ratios of two different second-order moments to the first-order moment of the pathlength distribution. It is plotted vs. optical depth for a uniform cloud (line) and for a more realistic stratified cloud (symbols) in a ground-based geometry. The upper curves are calculated ratios of the cloud thickness to mean pathlength. Ratio values measured with WAIL (see main text) are indicated by the lower dashed horizontal line, whose intersection with the lower curve gives the optical depth. From there, a vertical line to the upper curve yields the thickness Δ ; the mean pathlength was found to be approximately 1.37 km, yielding a physical cloud thickness of 0.52 km.

Consider now the well-known relation between optical depth and liquid water path (LWP), the vertical integral of LWC:¹⁰ $\tau = (3/2)LWP/\rho_w r_e$, where ρ_w is the density of liquid water (i.e., 10^6 g/m³). Thus, with an additional assumption on the effective droplet radius r_e , the volume-averaged LWC can be estimated using an optical WAIL measurement alone:

$$\overline{\text{LWC}} = LWP/H = (2/3) \rho_w (r_e/H) \tau; \quad (6)$$

no radiosondes, nor microwave instruments are required. For instance, taking $r_e \approx 10$ μm for simplicity, we find

$\overline{\text{LWC}} \approx 0.036$ g/m³ in our altostratus case. Thus we see that it is possible using WAIL data to determine cloud optical density, vertical thickness, and liquid water content.

4. SUMMARY AND ONGOING WORK

Wide-angle imaging lidar, is a significant new extension of lidar technology that can be used to determine cloud properties never before accessible to a purely optical measurement. We have shown that WAIL, and more generally off-beam lidar, can be used to measure both the physical thickness of a stratiform cloud and its optical depth at scales of about 0.5 km. In earlier work we demonstrated^{6,9} that similar information can be extracted from a non-imaging spaceborne lidar system with a wide-enough field of view, e.g., the shuttle-based LITE mission. Within instrumental and modeling error, both the “time-only” method used for LITE data and the “space-time” method presented here yield mutually consistent results. However, the combined space-time scheme, which calls for a device with imaging (or at least radial profiling) capability, provides a much less ambiguous measure of optical depth.

We have now obtained data both with our original MCP/CDL detector system, a custom LANL design described in some detail by Friedhorsky et al.,⁴ and with a commercial gated intensified CCD. The MCP/CDL detector has the advantages of high angular and temporal resolutions as well as extreme sensitivity. Its major disadvantage is the relatively low maximum allowable count rate, which necessitates co-adding many laser pulses in order to achieve good statistics on the scattered returns. The CCD system has the advantage of adjustable time gate widths, which allows the

wide dynamic range of cloud returns to be efficiently sampled. Its major disadvantage is that it obtains each time frame sequentially, with each frame requiring considerable integration time, and clouds can change in the course of the measurement.

While fully imaging WAIL provides a very exhaustive data set, extrapolation to a space-based system presents many technical challenges. Therefore, parallel to the WAIL project, collaborative work currently underway by Cahalan et al. at NASA Goddard Space Flight Center which is focused on a scheme using more conventional detectors fed by an optical train that is customized for airborne observation. In this design, known as THOR (for THickness from Off-beam Returns), the radial information is preserved but averaged azimuthally in the hardware, which incorporates fiber-optic bundles to route the light from pre-defined radial zones to several separate high-sensitivity photo-detectors. In March 2002, the two instruments were deployed simultaneously at the Oklahoma CART site, with WAIL probing the clouds from below in a ground-based measurement (the Fig. 2 data is from this exercise), and with THOR probing from above the clouds aboard a NASA P-3 aircraft. The resulting data sets, not yet fully analyzed, will provide an opportunity to directly verify the theory described here, with THOR providing direct cloud-top measurements and calculated cloud bottom positions, and WAIL providing direct cloud-bottom measurements and calculated cloud top positions.

Meanwhile, at LANL we are developing daylight capability for WAIL by means of an ultra-narrow magneto-optic filter coincident with strong solar Fraunhofer absorption lines. This filter uses Faraday rotation in sodium vapor to produce a 90-degree rotation of the plane of polarization for light propagating along the direction of the applied magnetic field. Placed between crossed polarizers, this results in an extremely narrow transmission band centered at the Na lines. Such Faraday filters have been described extensively in the literature.¹¹⁻¹⁶ Apart from their extreme narrowness and the convenient coincidence with the Na Fraunhofer lines, their most important feature for WAIL is that, unlike interference filters, their bandpass wavelength is nearly independent of the angle of incidence, at least for small angles. This is because the Faraday rotation is proportional to both the dot product of the direction of propagation and the B-field direct ($\sim \cos\theta$), and to the distance traveled through the Na vapor ($\sim 1/\cos\theta$), the two angular terms thus canceling.

We have built a sodium Faraday filter incorporating internal optics to provide a 65-degree external field of view while keeping the internal range of angles within the Na vapor cell to less than 20 degrees. Shown in Fig. 5, it uses SmCo permanent magnets to produce a 2700 gauss field inside the Na cell. The expected transmission characteristics, calculated using the model of Korevaar et al.,¹¹ are also shown in Fig. 5. Detailed verification of this curve is awaiting completion of the dye laser system that will be used as the transmitter in the daylight WAIL system.

Figure 5: Wide-angle Na Faraday atomic line filter. Left: photograph of the assembled filter with one its eight SmCo magnets partially withdrawn. Right: calculated transmittance of the filter; center wavelength is 589 nm.

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