LA-UR- 02- 1804 c.1

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Title: ACTIVE OPTICAL REMOTE SENSING OF DENSE CLOUDS WITH DIFFUSING LIGHT: EARLY RESULTS, PRESENT IMPLEMENTATIONS, AND THE CHALLENGES AHEAD

Author(s): Anthony B. Davis, Steven P. Love
Los Alamos National Laboratory (NIS-2)

Robert F. Cahalan, Matthew J. McGill
NASA - Goddard Space Flight Center

David M. Winker
NASA - Langley Research Center

Submitted to: IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2002),
Toronto (Canada), June 24-28, 2002.

02-1804

Active Optical Remote Sensing of Dense Clouds with Diffusing Light: Early Results, Present Implementations, and the Challenges Ahead

Anthony B. Davis, Steven P. Love
Los Alamos National Laboratory,
Los Alamos, NM 87545, USA

Robert F. Cahalan, Matthew J. McGill
NASA's Goddard Space Flight Center,
Greenbelt, Md 20771, USA

David M. Winker
NASA's Langley Research Center,
Hampton, Va 23681, USA

***Abstract*-We survey the rapid progress of "off-beam" cloud lidar, from inception to validation via laboratory-scale simulations. Cloud observations from ground, aircraft and even space are covered. Finally, we describe future work in this instrument development effort born out of pure theory in the mid-1990s.**

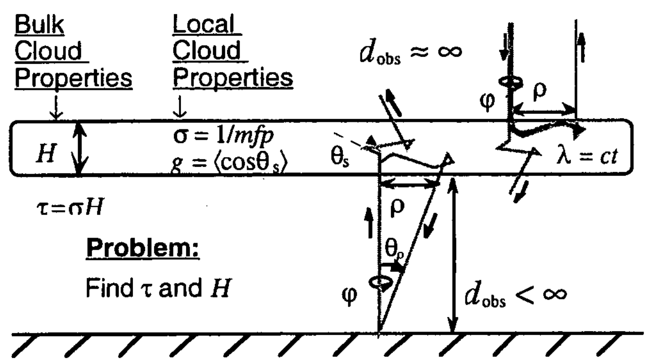
I. CONTEXT AND DEFINITIONS

Traditional "on-beam" lidar collects returns only from a very narrow field-of-view (FoV) centered on the transmitted laser beam. For remote sensing of cloud properties, this yields only a small fraction of the information potentially available. Indeed, at most optical wavelengths, laser photons are not absorbed but merely scattered out of the beam by cloud droplets, so they eventually escape the cloud after tens to hundreds or more scatterings. Much additional information is therefore available in the light scattered far from the input beam. Monitoring these "off-beam" returns in a sufficiently space- and time-resolved manner is the goal of instrument development under way at LANL and at NASA-Goddard. We call this generically "off-beam" cloud lidar.

II. GREEN FUNCTIONS AS OBSERVABLES

Off-beam lidars are effectively recording the cloud's radiative Green functions in space and/or time because the pulsed laser beam is a physical instance of a delta-function source. This insight tells us how to find what cloud information is contained in the off-beam signal. Green function theory is analytically tractable in photon diffusion approximation which is known to be valid for dense (hence primarily boundary-layer) clouds [1]. This early theoretical development [2] told us that both physical and optical thicknesses of the cloud layer can be inferred by off-beam techniques if they can sample the deep diffusion regime; more speculatively, one may be able to assess the degree internal variability (turbulence) of the cloud [3]. Figure 1 illustrates schematically off-beam lidar observations.

Green function theory [4] lead to an early validation using a slightly modified but otherwise standard research lidar [5]. In this exercise, the transmitted beam was deflected away from zenith and ever more highly scattered light was detected at zenith to an angular distance of 12 degrees. Time-integration and some pulse-averaging was used to defeat the solar background. Later, signal-to-noise ratio estimations [6] and down-scaled laboratory simulations with controlled "cloud" parameters [7], explained this success. This activity justified the effort of producing dedicated engineering models of off-beam lidars. In the systems we describe below, the transmitters are relatively standard but the receivers are not.



$$\langle\lambda\rangle = H\times[\,1+correction_1(g,\tau)\,]$$

$$\langle\lambda^2\rangle = H^2\times[(1-g)\tau]\times[\,1+correction_2(g,\tau)\,]$$

$$\langle\rho^2\rangle \approx H\times[mfp/(1-g)] = H^2/[(1-g)\tau]$$

Fig. 1. Schematic of off-beam cloud lidar observation geometry *without* any vertical exaggeration. Extinction σ defines the photon mean-free-path (mfp) and appears in optical depth τ. The presently proposed retrieval methods use low-order statistical moments, denoted by angular brackets, of the detailed signal unfolding in space (angle) and time (in-cloud path length).

III. GROUND-BASED INSTRUMENT

The LANL prototype, Wide Angle Imaging Lidar (WAIL), is a ground-based concept that has already been fielded several times [8]. It incorporates a high-speed micro-channel-plate (MCP) imaging detector system at the 2-inch focal plane of a simple camera lens with 60-degree full-angle FoV. This FoV —rather extraordinary by atmospheric lidar standards— is required to capture the full width of the reflected Green function for a typical dense cloud (optical depths in excess of 10) at a range of about 1 km. WAIL, in effect, produces "movies" of the dynamic scattering process across cloud base.

Figure 2 shows four representative "stills" from two associated WAIL data-cubes on a cloud of opportunity. The top row uses a 10-nm band-pass interference filter centered at the transmitter wavelength (532 nm) which has the effect of emphasizing the bright central part of the evolving light field; several neutral filters were also in place to avoid detector saturation. The bottom row uses an off-set interference filter that defeats (but not entirely) the bright central peak and emphasizes the faint far field of purely diffusing light.

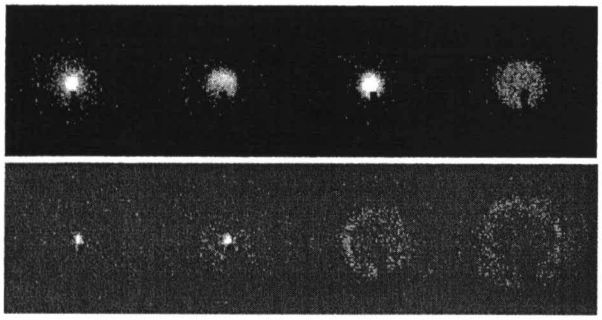


Fig. 2. Four "scenes" from a WAIL "movie". For more information on the instrument, this particular field observation and others (including laboratory-scale mock-ups), see the URLs <http://nis-www.lanl.gov/~love/clouds.html> and <http://www.rulli.lanl.gov/cloud/cloud.htm>.

IV. AIRBORNE INSTRUMENT

The GSFC prototype, cloud THickness from Off-beam Returns (THOR) lidar, has a compact and robust design for airborne deployment where imaging is abandoned in favor of obtaining a radial profile of the diffuse "spot" excited by the transmitted beam. Azimuthal integration is done in hardware at the 1-inch focal plane of the custom optics with a 6° full-angle FoV. This is the entry point of a massive fiber-optic bundle; by subdivision, the bundle feeds 10 photo-multiplier tubes (PMTs) that deliver the pulse-shapes collected in 8 concentric annuli with exponentially increasing diameters. For mechanical reasons, the outer annulus is subdivided into three 120-degree azimuth sectors which, in turn, enables a first-order estimation of cloud heterogeneity effects.

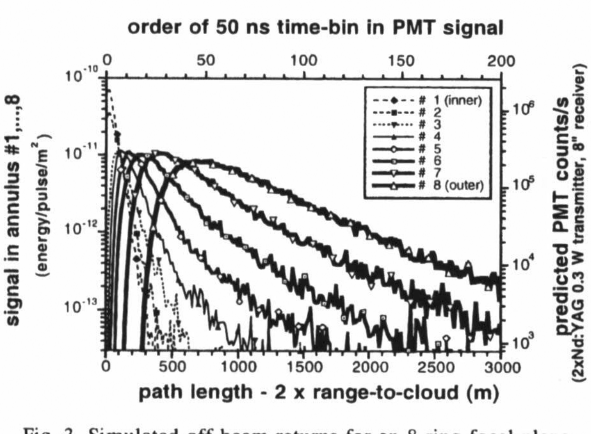


Fig. 3. Simulated off-beam returns for an 8-ring focal-plane configuration. Airborne THOR observation: cloud top at 9 km range (i.e., about 1 km altitude), and 6° FOV. The cloud is assumed vertically stratified and horizontally uniform in extinction: extinction $\sigma(z)$ grows as the power 0.35 of the distance from cloud base; optical thickness is $\tau = \int\sigma(z)dz = 15$.

Figure 3 shows the outcome of a numerical simulation of THOR signals (with channels 8-10 summed) for a stratified cloud with structural and optical parameters that we expect to observe quite frequently. The near-beam signal decays exponentially with a time-scale on the order of the mean-free-path at cloud top. The off-beam signal decays much more slowly, essentially on the scale of the cloud's thickness, taken here to be 0.5 km. Note that anticipated photon noise, square-root of counts on right-hand axis (by near new-moon night), is much less than the numerical (Monte Carlo) noise present here.

V. "OFF-BEAM" LIDAR IN SPACE? DONE THAT!

Interestingly, there has already been a non-imaging incarnation of off-beam lidar in space: NASA's Lidar-In-space technology Experiment (LITE) that flew on the Space Shuttle in 1994. Indeed, the unusual (260 km) range to cloud top of an otherwise relatively standard lidar system enabled the collection of all orders of scattering in the 3.5 mrad FoV since its foot-print was 0.91 km. The target for (night-time) orbit 135 was an extended and persistent strato-cumulus deck.

Figure 4 shows LITE returns from such dense clouds. Notice the exponential decay on the time-scale of the light-travel time through the cloud's physical thickness. This exponential tail is readily reproduced in numerical simulations, both by Monte Carlo solution of the time-dependent radiative transfer equation [9] and detailed diffusion theory [3,5]. This characteristic, and easily measured, feature is not yet fully explained theoretically from first principles and mathematical analysis, but we are close [10].

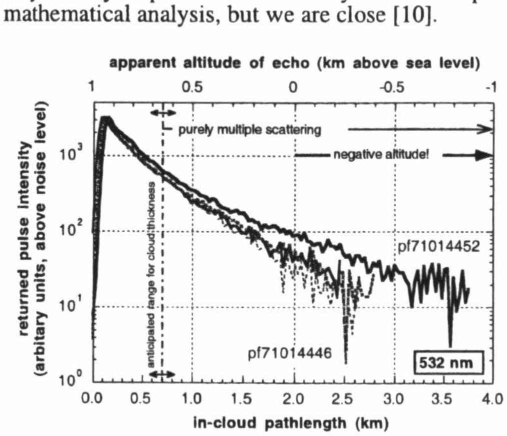


Fig. 4. Four non-saturated pulses from dense marine stratocumulus observed during NASA's LITE mission in 9/94.

We have no spatial/angular information here, only in time. It can however easily be shown [11] that the 1st- and 2nd-order moments of the in-cloud photon path depend differently on the basic cloud parameters, cf. Fig. 1. We proceeded to demonstrate [12] that cloud property retrievals using LITE's temporal Green function observations in Fig. 4 compare quite favorably with climatology for such clouds.

VI. NEAR-FUTURE PROJECTS

A major THOR/WAIL validation campaign is planned for late March 2002 out of Wichita (Ks) for THOR flights and above DOE's Atmospheric Radiation Measurement (ARM) instrument site in Lamont (Ok), where WAIL will be relocated. So far, THOR has performed well in the laboratory and on the ground but its FoV is designed for a 10-or-so km range. We are looking forward to its first test-flight. So far, WAIL has been using a custom focal plane detector [13] developed for other programs at LANL. It has just been re-configured with a new (commercially available) focal-plane detector which needs to be tested in the field. Furthermore, cloud quantities obtained from either off-beam instrument have been compared with other established cloud-probing instruments.

The next major challenge in off-beam cloud lidar is to extending capability to the full diurnal cycle without sacrificing too much on spatial or temporal resolution. We are currently exploring how to do this by means of using ultra-narrow magneto-optic filters [14] that operate at the wavelengths of the well-known atomic sodium doublet. Apart from the inherent noise reduction, the Sun is actually quite dark in the Na lines, hence its already routine utilization in fluorescence lidar for mesospheric diagnostics.

VII. SUMMARY AND OUTLOOK

We foresee a bright future for off-beam lidar which is, in essence, an atmospheric application of the general principles of optical diffuse-light tomography [15]. The physical cloud-boundary information it delivers is, in principle, the same as given from ground or space (upcoming CloudSat mission) obtained by mm-radar. And mm-radar gives some information about internal variability. However, radar reflectivities quite often disagree with optical estimates of cloud base and optical thickness for well-understood reasons [16]. So optical and microwave cloud probes are now considered as complimentary rather then competitive in our efforts to better understand cloud radiative properties in the context of climate research. We are confident that off-beam lidar will be a valuable and, ultimately, cost-effective source of information about cloud processes. In this, we include direct insight into the present issues in large-scale short-wave absorption [17] based on unambiguous geometrical path-length statistics, a unique capability of off-beam cloud lidar.

ACKNOWLEDGMENTS

The LANL portion of this work is supported by the Laboratory Director's Research and Development (LDRD) program, under an "Exploratory Research" project. We thank A. Bird, D. Casperson, C. Ho, C. Rohde, R. Smith and L. Tellier for detector expertise and assistance with WAIL data collection. The GSFC portion of this work is supported by the Director's Discretionary Funds (DDF) program for instrument development, executed largely by John Kolasinski to whom we are greatly indebted. We thank Mark Vaughan for help in accessing the raw LITE data. We also thank Drs. S. Gerstl, H. Melfi, A. Marshak, I. Polonsky, W. Priedhorsky, J. Spinhirne, J. Weinman, W. Wiscombe, and E. Zege for many fruitful discussions that have helped shape the photon diffusion approach to cloud lidar probing and its implementation in WAIL and THOR.

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