Wide Angle Imaging Lidar: Active Optical Sensor Technology for Ground-Based Probing of Dense Clouds

Contributors
Anthony B. Davis, *Los Alamos National Laboratory*

Research Highlight

Standard atmospheric lidar observations are predicated on the single-scattering solution of the time-dependent radiative transfer equation where the source and observation angles share the same vertical axis, but in opposite directions. This implies a priori that the column must be optically thin, i.e., free of clouds (except for thin cirrus and similar clouds). Therefore, the main contribution of "on-beam" ground-based lidar to cloud remote sensing is accurate cloud-base height determination (a.k.a., ceilometry; see left-hand side of schematic in Fig. 1 and Fig. 2.) We have contended, starting speculatively [Davis et al. 1997], that this limitation of classic lidar vanishes when one turns to the opposite asymptotic regime in radiative transfer: diffusion theory. This is the limit where the mean-free-path (MFP) is small compared to the outer dimensions of the highly scattering medium (see right-hand side of schematic in Fig. 1 and Fig. 2.) However, can the weak "off-beam" returns of multiply scattered laser light be observed? If so, can they be utilized for cloud property retrievals? If so, how does this emerging optical technique compare with well-established millimeter cloud radar (MMCR)? MMCR is the exact single-scattering equivalent of lidar for clouds, which may be optically thick in the solar and thermal regions of the spectrum... but not for mm-waves.

A series of theoretical [Davis et al. 1999, Polonsky and Davis 2004, Davis 2007] and observational [Davis et al. 1999, Love et al. 2001, 2002, Polonsky et al. 2005] studies demonstrated the feasibility of multiple-scattering cloud lidar that is characterized most notably by exceptionally wide fields-of-view (FOVs).

A critical milestone was reached by Polonsky et al. [2005] who analyzed data collected when the Los Alamos National Laboratory's (LANL's) Wide Angle Imaging Lidar (WAIL) system was deployed on the visitor's platform of the Central Facility at the ARM Climate Research Facility (ACRF) Southern Great Plains (SGP) site in Lamont, Oklahoma, in March 2002. Figure 3 shows the engineering model in action. These authors were able to compare their retrievals of physical cloud thickness, hence cloud top height (Fig. 4), and cloud optical depth (Fig. 5) with those obtained from ARM's operational cloud products from the MMCR and passive microwave radiometers (MWRs). We note the cloud optical depth of 20 to 30, completely inaccessible to on-beam lidars. The retrieval scheme they used was a straightforward least-squares fit of WAIL observations with Polonsky and Davis' [2004] diffusion-theoretical forward model for the WAIL signal. Raw WAIL data are shown as a "movie" that captures the remotely observable space-time radiative Green function excited by the pulsed laser, in essence a Dirac delta-source. (Download examples of WAIL movies [MPG, 25Mb] with audio commentary.) As it turns out, ARM cloud parameters fall well within the error bars estimated for WAIL's retrievals. These error bars can be reduced significantly by widening the FOV and thus capturing more of the far-field tail of the Green function.

From other publications, we note that Davis et al. [1999] showed that the time-integrated off-beam lidar signal was detected in broad daylight using a

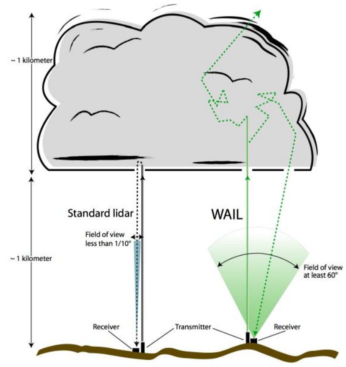

Figure 1. Lidar observations of a dense cloud. Left: standard (single-scattering/on-beam) lidar. Right: multiple-scattering/off-beam lidar. Note the extreme narrowness of the FOV in the standard case, as is required to restrict as much as possible the signal to a single backscatter. Also note the weak penetration, O(1) MFP, of the two-way transmitted beam. In strong contrast, off-beam lidar requires a very wide FOV that captures all orders of scattering in the reflected laser light. In the schematic, we see beams undergoing 8 to 9 scatterings before being transmitted or reflected; these scatterings are isotropic, but the (so-called "transport") MFP between them is accordingly longer: ~7 times the normal MFP and, implicitly, that many more forward-peaked scatterings. The ideal FOV for WAIL is somewhat larger than the radiative smoothing scale, the harmonic mean of cloud thickness and transport MFP, also the inherent spatial resolution of WAIL retrievals.

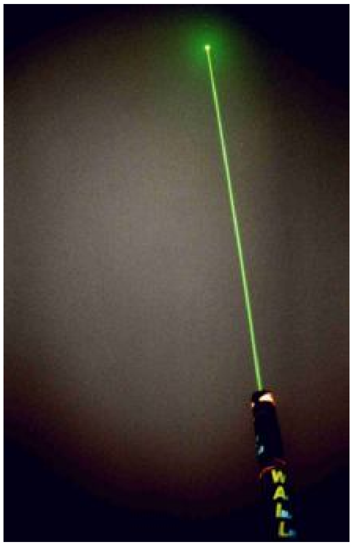

Figure 2. WAIL's green beam. The 532-nm ~5-W laser beam hits the cloud base a few 100 meters above ground. A faint but discernable halo of green light can be seen around the beam, the most central part of the

slightly modified research lidar system used for ground-based observations at the National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center (GSFC). Love et al. [2001] used an alternate imaging detector technology on a cloud of opportunity in New Mexico; they also describe a moment-based retrieval scheme that can be invoked when the FOV is large enough, and/or the ceiling high enough, to image the tail of the Green function. Love et al. [2002] describe a comprehensive approach to solar background suppression based on ultra-narrow magneto optic filtering technology that preserves potentially the entire WAIL signal.

Finally, we note that two other groups are developing airborne instrument systems for dense cloud probing based on the same signal physics as WAIL but diverge significantly in hardware implementation, as well as in data processing. The two designs also differ strongly between each other in stand-off distance to the cloud: NASA-GSFC's [cloud] THickness from Off-beam Returns (THOR) operates nominally from ~10 km above cloud top while the "in-situ" cloud lidar by University of Colorado and SPEC, Inc., operates inside the cloud.

Wide-FOV/multiple-scattering lidar is a promising new technology for cloud remote sensing from ground, WAIL being the prototype, as well as space. It complements MMCR and single-scattering lidar by using completely independent means to determine the cloud's geometrical thickness and its optical depth at the laser wavelength (i.e., in the climatically important short-wave spectrum). WAIL's estimates of these cloud parameters are naturally volume-averaged at the radiative smoothing scale, a key cross-over from full 3D radiation transport regimes to one where the popular independent column approximation (IPA) is applicable. Last, but not least, multiple-scattering cloud lidar retrievals make no assumptions about cloud microphysics, which is another way the new technology complements existing MMCR and MWR systems.

Additional Journal References:

Davis, A., A. Marshak, R. F. Cahalan, and W. J. Wiscombe, 1997: The LANDSAT scale-break in stratocumulus as a three-dimensional radiative transfer effect, Implications for cloud remote sensing, **J. Atmos. Sci.**, 54, 241-260.

Davis, A. B., R. F. Cahalan, J. D. Spinhirne, M. J. McGill, and S. P. Love, 1999: Off-beam lidar: An emerging technique in cloud remote sensing based on radiative Green-function theory in the diffusion domain, **Phys. Chem. Earth** (B), 24, 177-185 (Erratum 757-765).

Love, S. P., A. B. Davis, C. A. Rohde, L. Tellier, and C. Ho, 2002: Active probing of cloud multiple scattering, optical depth, vertical thickness, and liquid water content using Wide-Angle Imaging Lidar, **S.P.I.E. Proc.**, 4815, 129-138.

Love, S. P., A. B. Davis, C. Ho, and C. A. Rohde, 2001: Remote sensing of cloud thickness and liquid water content with Wide-Angle Imaging Lidar (WAIL), **Atm. Res.**, 59-60, 295-312.

excited Green function; the strong background is transmitted light from a near-full moon.

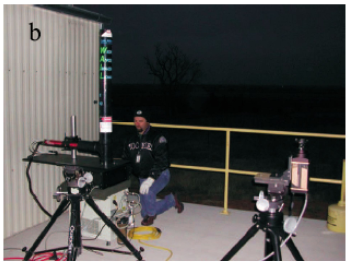

Figure 3. WAIL deployed at the ARM SGP site. On the left-hand side, we see the water-cooled laser transmitter (Cutting Edge Optronics "Stilletto"), which is a frequency-doubled solid-state Nd:YAG system; its more important specs are 532-nm wavelength, ~0.5-mJ/pulse, and 4- to 12-kHz rep-rate. On the right hand- side, we see the gated/intensified CCD camera (Roper Scientific "PI-Max") outfitted with a lens yielding 54 degrees FOV (full-width) at the focal plane; its most interesting feature for the WAIL application is the option of fully programmable time binning to accommodate the large dynamic scale in the multiple-scattering signal from early to late delays.

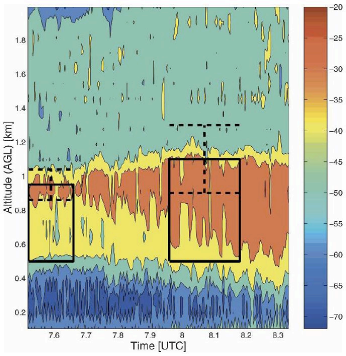

Figure 4. Cloud reflectivity as a function of time and altitude above ground level (AGL) from the MMCR. The layer with a strong reflectivity (cf. dBZ scale at the right side) is situated between ~0.4 and ~1.1 km. Rectangles show the location of the cloud inferred from WAIL data (and the duration of the 3-filter collection described in full detail by Polonsky et al. [2005]), while the dashed lines depict uncertainties in the cloud-top estimation. The magnitude of the uncertainty in cloud-top determination (reflecting uncertainty in retrieved cloud thickness) was traced to the insufficient FOV (even at 54 degrees full-width) to capture the spatial tail of the radiative Green function.

Polonsky, I. N., and A. B. Davis, 2004: Lateral photon transport in dense scattering and weakly-absorbing media of finite thickness: Asymptotic analysis of the space-time Green function, **J. Opt. Soc. Am. A**, 21, 1018-1025.

Polonsky, I. N., S. P. Love, and A. B. Davis, 2005: The Wide-Angle Imaging Lidar (WAIL) deployment at the ARM Southern Great Plains site: Intercomparison of cloud property retrievals, **J. Atmos.** and **Oceanic Techn.**, 22, 628-648.

Reference(s)

Davis, AB. 2008. "Multiple-scattering lidar from both sides of the clouds: Addressing internal structure." Journal of Geophysical Research 113, D14S10, doi:10.1029/2007JD009666.

Working Group(s)

Cloud Properties

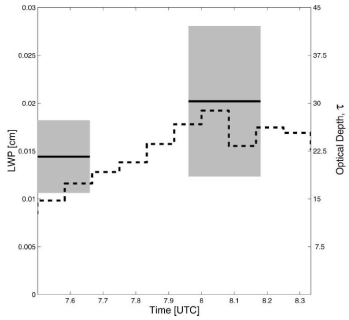

Figure 5. Cloud liquid water path (left) and optical thickness (right) as functions of time. Estimation of optical thickness from the MWR data (dashed line) may have as much as a 20% error due to uncertainty on the effective droplet radius (set here, for simplicity, to 10 microns). Solid horizontal lines show optical thickness retrievals from WAIL, the gray rectangles indicating their inherent least-squares uncertainty. Taking WAIL's cloud optical depth together with the MWR's LWP would lower the effective droplet radius to ~9 microns. Here again, it was determined that the magnitude of the uncertainties can be reduced significantly by acquiring a larger FOV either optically or mechanically. In the later scenario, the imaging detector's optical axis is tilted away from the vertical laser beam axis (without losing from the image the impact point of the beam on cloud base).