Wide-Angle Imaging Lidar (WAIL) for Active Cloud Probing: Instrument Enhancements and New Data Analyses

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WAIL is the ground-based progenitor of a new class of active cloud probes that also includes the airborne THickness from Off-beam Returns (THOR) system developed at NASA Goddard and the in-cloud lidar developed by the U. of Colorado and SPEC. This class of instruments exploits the highly scattered light from a pulsed laser illuminating the cloud at a non-absorbing wavelength, and can probe optically thick clouds using VIS-NIR light which in traditional lidar is all but extinguished (i.e. scattered out of the beam) within a few mean-free-paths. In contrast with the direct beam, the multiple-scattering Green function probed by WAIL permeates the whole cloud. Thus, both the physical thickness of the cloudy medium and its optical thickness (equivalently, volume-averaged extinction) can be determined from the spatial and temporal data. Collectively, these new instruments rejuvenate optical cloud remote sensing at a time when ambitious climate monitoring programs such as ARM have identified the need for breakthrough in observational techniques to reach their common goal to advance predictive climate science. Both WAIL hardware and analysis methodology have evolved in the last year or so towards a configuration where it can sooner be incorporated into cloud instrument suites at ARM facilities.

In 2002, WAIL and THOR were deployed simultaneously at the SGP CART site in a mutual validation exercise. While successfully demonstrating the power of the off-beam lidar concept and validating retrieval algorithms, this experiment also highlighted some aspects of the hardware that could be improved.

Figure 2. The WAIL/THOR cross-validation experiment. WAIL operated from the ground and thus provided a direct measurement of the cloud base height; THOR, airborne above the cloud, similarly provides a direct measurement of the cloud top height. Each could thus verify the other's derived far-side interface position determination. At right is a photograph showing the WAIL instrument deployed at the SGP CART site. The laser transmitter is a doubled Nd:YAG (532 nm) operating at a repetition rate of 4 to 12 kHz, a 30 ns pulse width, and roughly 4W average power. The receiver is a gated intensified CCD camera with a time resolution as fast a 1 ns (we typically use 50 ns or longer). A WAIL "movie" is collected by sequentially advancing the CCD's gate delay w.r.t. the laser pulse.
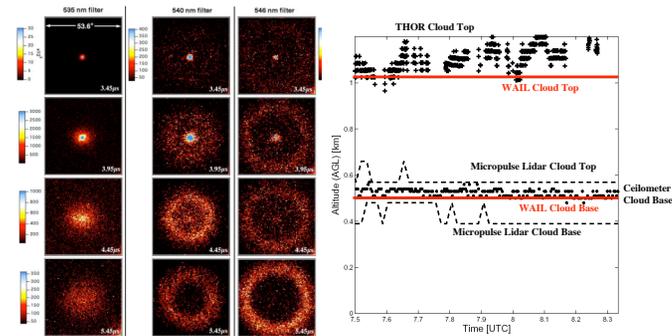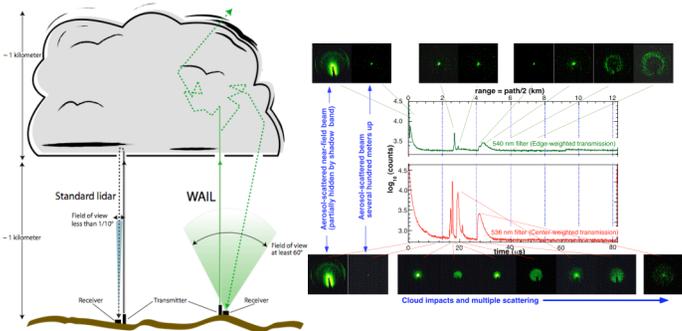
Figure 1. The Wide-Angle Imaging Lidar (WAIL) concept, contrasted with standard lidar. Standard lidar collects returning light from only a very narrow angular range about the laser beam; light scattered out of the beam is intentionally ignored and is considered to be extinguished. For optically dense clouds, this limits standard lidar to measuring the range to the cloud bottom. WAIL, in contrast, focuses its attention specifically on the light scattered out of the beam, taking high-speed, wide-angle "movies" of the spatial distribution of returning light as a function of time after the laser pulse. This multiply scattered light samples the interior of even optically dense clouds, all the way to the top of the cloud. By measuring both the spatial and temporal distributions of returning light, WAIL can determine both the physical thickness and optical density of the cloud, and hence estimate liquid water content. At right is some typical early WAIL data, with images above and below showing the spatial distribution of returning light at various times after the laser pulse, modified by the spatial response of the background-suppression interference filters. Each image spans approximately 60°. Graphs show the spatially-integrated signal as a function of time. The cloud deck for this example was rather complex, consisting of several thin layers beneath a denser upper layer.
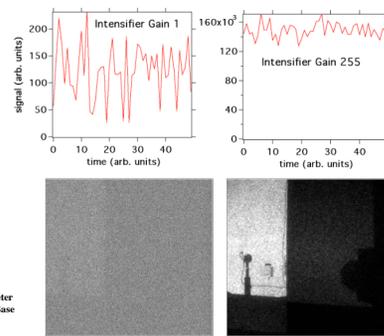
Figure 3. WAIL data and retrieved cloud thickness validation. Left: Sample frames from WAIL datasets obtained at the Oklahoma CART site during the WAIL/THOR cross-validation experiment in March 2002. Shown here are sequences obtained using three different background suppression filters that optimize for different ranges of observation angle. The first (535 nm band center) emphasizes the central region, the second (540 nm) emphasizes intermediate angles, and the third (546 nm) emphasizes large angles. Time delay after the laser pulse is noted on each frame. In this 2002 implementation of WAIL, a complete dataset is obtained only after combining these three restricted-angle sets. This rather awkward procedure prompted us to re-evaluate the need for such narrow-band interference filters. Our revised instrument uses a wider-bandpass filter, enabling us to capture the full angular range at once. Right: Comparison of cloud top and cloud bottom positions determined by WAIL and THOR, as well as by the CART site's micropulse lidar and ceilometer, showing excellent agreement between the WAIL and THOR direct and derived cloud interface positions.

Figure 4. WAIL enhancements: Wider bandpass and wider field of view. Two things became apparent during the WAIL/THOR experiment: (1) The 53.6° field of view, though "wide," wasn't wide enough for the low cloud ceilings during that campaign, leading to truncation of our spatial distribution data. This necessitated abandoning our moment-based analysis and inventing a new retrieval method [Polonsky, et al. 2005]. (2) Our use of very narrow-band background suppression filters necessitated an awkward dataset splicing process, but in practice, background light wasn't really a limiting factor in a typical rural environment. So an obvious improvement is to increase the f.o.v. and avoid the splicing by widening the bandpass. These two laboratory images, illuminated by diffusely-scattered 532nm laser light, compare the angular acceptance of our old system (with 10nm-bandpass filter at 540nm displaying annular acceptance) on the left, and the new system (with 50nm bandpass filter admitting the entire angular range) on the right. Fields of view are 53.6° square and 88.3° square, respectively.

Figure 5. SNR enhancement using image intensifier. WAIL's gated CCD is equipped with an image intensifier that, at least for the extremely dim long-time, large-scattering-angle returns, offers significant SNR improvement. Here we show a laboratory test comparing a very weak optical signal imaged with no intensification on the left, and maximum intensification on the right. Artifacts make intensification less desirable for stronger signals.
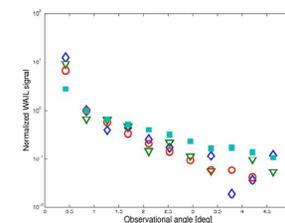
Figure 6. New Analysis Techniques. Here we show the angular dependence of the normalized WAIL signal for selected time-slices mapped to altitudes above ground. Below the cloud, we have 180 m (◇), 293 m (▽), and 406 m (○). Notice that for the in-cloud range of 594 m (■) this angularly-resolved signal is significantly flatter than for the below-cloud ranges. The multiple-scattering retrieval method by Bissonnette et al. [2005], based on the small-angle approximation, will enable us to extract new information about both aerosol and cloud particle size distributions from these near-axis WAIL data.

References
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