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Final Report

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Development of High Spectral Resolution Lidar (HSRL) Technology

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1 Introduction

This report describes progress achieved during two years of DOE funding provided by grant DE-FG02-90ER61058. This grant was titled "Development of High Spectral Resolution Lidar Technology for use in the DOE ARM Program". Nearly all grant objectives were achieved despite the fact that DOE abruptly canceled funding after only two years of a planned three year effort. The principal investigator learned of the cancellation only after attempting to determine why third year funding had not arrived. This occurred two weeks into the planned third year. The unexpected loss of funds created destructive dislocations in our research program.

This report describes only progress during the two funded years. Subsequent research, funded by other sources, has resulted in High Spectral Lidar System performance well in excess of that proposed in the DOE program. This system has proven its performance in routine observations at the University of Wisconsin and during an extended field deployment as part of a winter storms project in Arizona.

2 Report

Under this grant the HSRL was completely redesigned, and rebuilt for operation in an electronics van. A new mechanical structure and active thermal control has largely eliminated the calibration drift which required a multi-hour warm up period before the previous system could provide measurements. A new data system based on a Sun workstation and an Intel i960 preprocessor allows easy operator control of this complex system and provides the most advanced realtime data display system currently used on any lidar. A new photon counting system has been designed for the HSRL. These counters accept maximum count rates of ~ 1 GHz in bin widths as short a 100 ns; these specification far exceed those of commercially available units (additional system details are available in appendix A).

While the previous HSRL provided profiles to a maximum altitude of ~ 14 km, the new system routinely extends this to 20 km and with extended integration times provides profiles to an altitude of 30 km.

The HSRL provides calibrated profiles of atmospheric scattering properties. These profiles are direct measurements which do not rely on assumptions about the composition, sizes or shapes of the atmospheric scattering particles. In addition the HSRL has a very large dynamic range such that intense scattering from cloud layers can be measured in the same profile with the aerosol scattering from some of the cleanest tropospheric layers. This capability is illustrated in Figure 1 where aerosol backscatter ratios and backscatter cross sections are presented.

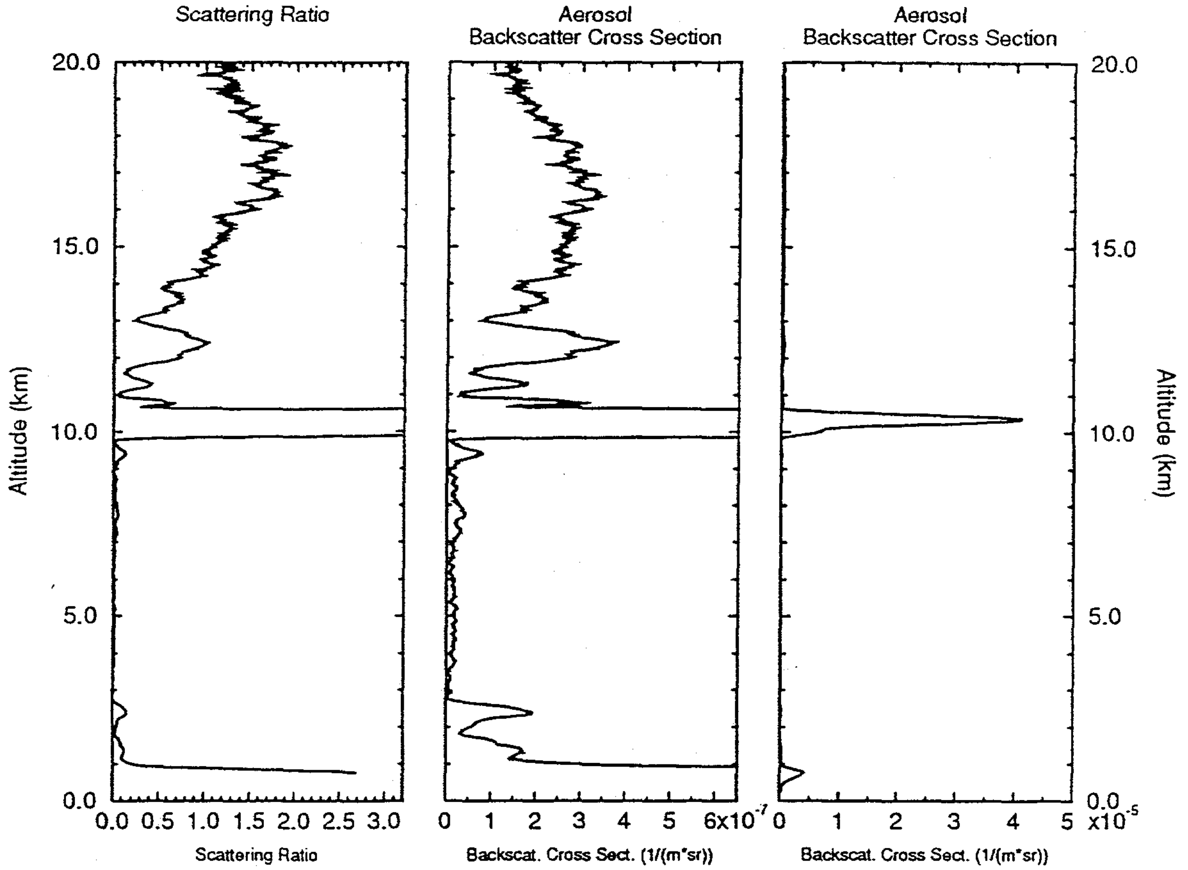

Figure 1. Vertical profiles of the lidar backscatter ratio, $\mathcal{R}$, backscatter cross section, $\frac{\beta_a(z)\mathcal{P}(\pi,z)}{4\pi}$ measured on 12-Dec-1992 with the HSRL. Note the cirrus cloud at an altitude of 10 km and the stratospheric aerosol from the Mount Pinatubo volcano between 11 and 20 km. A layer of tropospheric aerosol is also visible below 3 km. The backscatter cross section in the cirrus cloud is $\sim 4x10^4$ times larger than that in the upper troposphere. The scale in center panel has been selected to show details of the aerosol scattering profile. The right hand panel shows the backscatter cross section profile from the central panel plotted to show the peak scattering from the cirrus cloud. Notice that this does not represent a separate measurement; just a rescaling of the center plot.

The HSRL measures the vertical profile of the optical depth. The large dynamic range of the system and sensitivity of the system allow single profiles to cover the altitude range from $\sim$ 2.5 km to 20 km. The lower limit of these profiles is currently limited by a range dependence of the calibration coefficients at close ranges where light from the outer part of the receiving telescope fails to reach the detector. Modifications now in progress promise to reduce the minimum range to $\sim$ 400 m. Figure 2 provides an example of an optical depth profile measured with the new system.

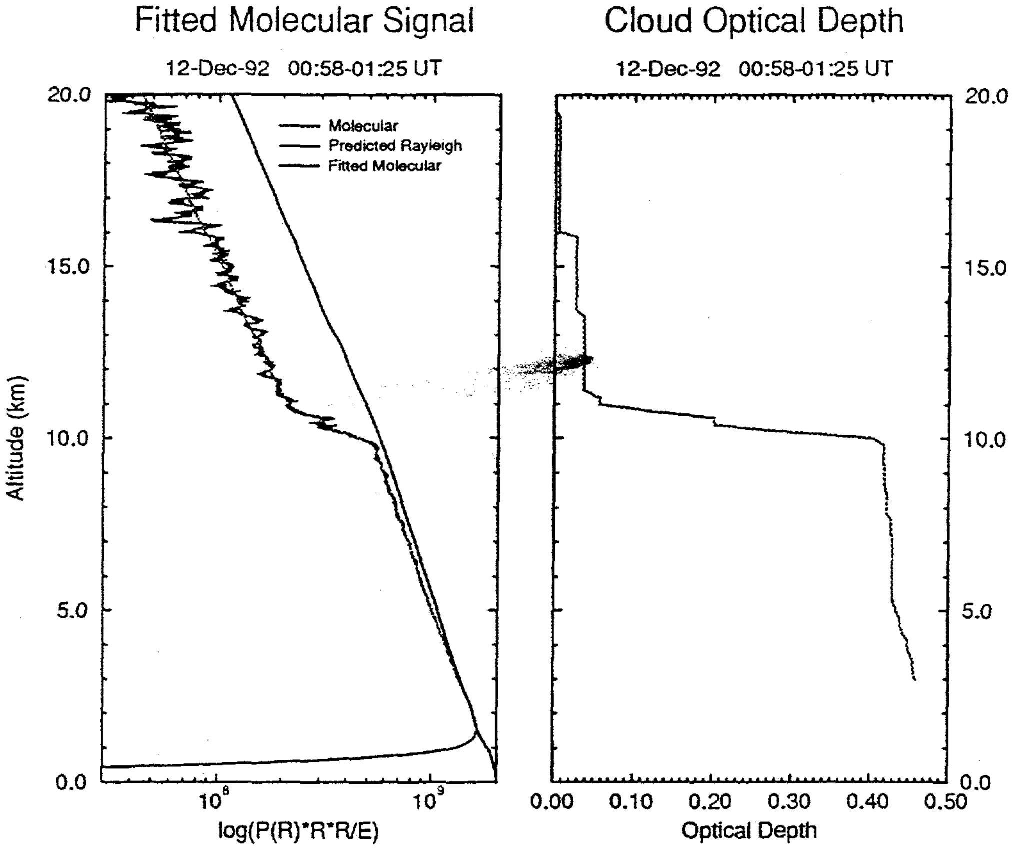

Figure 2. Lidar returns from the molecular atmosphere and the optical depth profile for the same data used to produce figure 1. The left panel shows the molecular profile observed with the HSRL along with a molecular lidar return computed using a temperature profile from the nearest National Weather Service temperature profile. The difference between the computed profile and the observed profile is due to aerosol attenuation. The right panel shows the aerosol optical depth profile measured below 20 km. This was obtained by subtracting the Rayleigh optical depth profile from the total optical depth computed from equation 6. In order to reduce fluctuations in the optical depth profile, the molecular profile is smoothed with a constrained least squares fit before computation of the optical depth. Figure 4 provides estimates of the reliability of these measurements

The new HSRL configuration provides a unique design for measuring the depolarization of the lidar return. Traditional systems use polarization beam splitters in the receiver to direct orthogonal linear polarizations to two separate detectors. This requires that the optical transmission of each channel and the gain of the two photodetectors be measured in order to measure the depolarization ratio. The HSRL uses a single detector for both polarizations. This is accomplished by transmitting alternate laser pulses with vertical and horizontal polarizations. A single linear polarization filter and a single detector can then be used and the depolarization ratio can be computed between alternate laser pulses. The 4 kHz pulse repetition rate of the system prevents the atmosphere from changing between pulses. This yields very precise depolarization measurements. Furthermore, since the HSRL separates the lidar return into aerosol and molecular returns the depolarization of both components can be measured separately (see appendix A for more details).

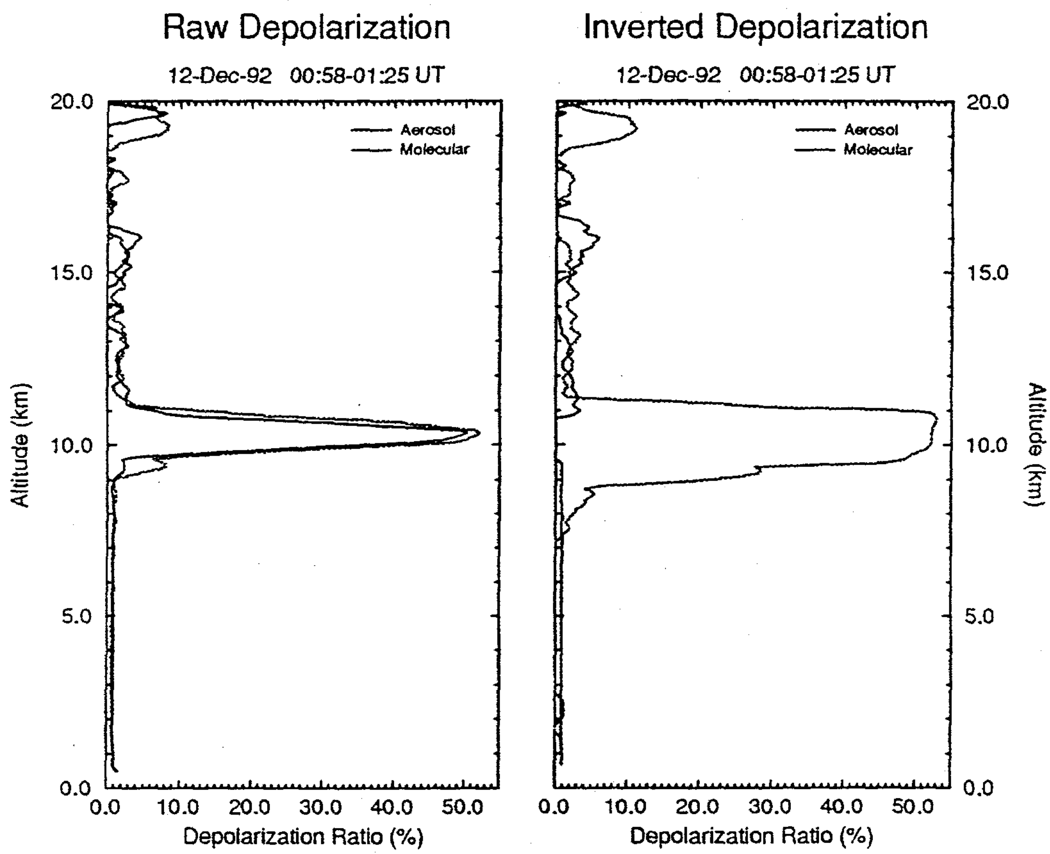

Figure 3. HSRL depolarizations measured in the molecular and aeros ol channels(left hand panel) and the separated depolarizations for aerosol and molecular scattering(right hand panel). Notice the large depolarization produced by the cirrus cloud. Also notice that the separated molecular depolarization show the small depolarization characteristic of Cabanne line scattering from air molecules. This profile does not include a water cloud, however, in other returns containing water clouds the depolarization is typically $< 2\%$. The HSRL provides very precise depolarization measurements because the same detector and optical path is used for both polarization components. Measurements of the molecular depolarization are measured to be between 0.6 and 0.8%; this compares with a theoretical value of 0.47%. Calibration tests indicate the residual depolarization produced by the instrument can be ultimately reduced to $\sim 0.1\%$.

Lidar results are typically analyzed using an equation which assumes all photons contributing to the return have been singly scattered. Lidar pulses returned from clouds often encounter large optical depths within a short distance of the cloud boundary and many of the received photons are likely to result from multiple scattering. As part of the work supported by ARM we have developed an improved model for the calculation of multiply scattered contributions to a lidar return (see appendix B). The multiply scattered lidar signal is a function of receiver field of view, particle size, range from the lidar and optical depth. The new HSRL includes a separate channel to measure the lidar return as a function of receiver field of view. Since the other quantities are measured directly by the HSRL we expect that observations with this channel will lead to remote measurements of cloud particle size.

Progress on this research has been reported in the following scientific papers:

- *University of Wisconsin Cirrus Remote Sensing Experiment* by S. A. Ackerman, E. W. Eloranta, C. J. Grund, R. O. Knuteson, H. E. Revercomb, W. L. Smith and D. P. Wylie. This paper has been accepted for publication by the Bulletin of the American Meteorological Society.

- *A Practical Model for the Calculation of Multiply Scattered Lidar Returns* by E. W. Eloranta. Presented at the Optical Society of America t opical meeting on Remote Sensing of the Atmosphere, Salt Lake City, UT. March 1993. An extended abstract is attached as appendix B.

- *Initial Data from a New High Spectral Resolution Lidar* by E. W. Eloranta and P. K. Piironen. Presented at the Optical Society of America topical meeting on Remote Sensing of the Atmosphere, Salt Lake City, UT, March 1993. An extended abstract of is attached as appendix A.

- *Adaptation of the University of Wisconsin High Spectral Resolution Lidar for Use in the ARM Program* by E. W. Eloranta and P. K. Piironen. Presented at the Annual Meeting of the American Meteorological Society, Anaheim, CA, January 1993.

App. A and B removed for processing separately (cnts)