June 2012

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Upgraded ALO Rayleigh Lidar System and Its Improved Gravity Wave Measurements
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Introduction
We have recently made the first measurements with the new, very large Rayleigh-scatter lidar system at the Atmospheric Lidar Observatory (ALO) at Utah State University in Logan, Utah. The new system is an upgraded version of the original Rayleigh lidar that operated at ALO from 1993 to 2004. With the new system the observational altitude upper limit has increased and the resolutions in the reduced data have become finer. These improvements to the data will have significant impacts on the study of atmospheric gravity waves and other middle-atmosphere phenomena.

System Background
The much larger ALO Rayleigh-scatter lidar combines two Nd:YAG lasers to achieve a total laser power output of 42 W at 532 nm. The lasers are pulsed at 30 Hz and frequency-doubled from a wavelength of 1064 nm to output at 532 nm. This wavelength was chosen to take advantage of the largest Rayleigh scatter cross section. Photons emitted from the laser are backscattered in the middle atmosphere and collected by four 1.25 m diameter parabolic mirrors, equivalent to one 2.50 m diameter mirror. These mirrors focus the returned photons into optical fibers that, in combination with detector optics, transmit the photons to a photomultiplier tube (PMT). From there, a multi-channel scalar (MCS) unit and its software package count the photoelectrons and record them to a PC.

Raw Data Comparison
The increased sensitivity of the new system is evident in the raw data, seen as the average number of photoelectrons counted in two minutes. As can be seen in Figure 2, the new, large Rayleigh lidar detects, so far approximately 30 times more photoelectrons than the original system in raw data collection. This increased sensitivity enables data to be acquired to greater altitudes and analyzed with better resolutions and precision.

Table 1. ALO Rayleigh Lidar Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>532 nm</td>
</tr>
<tr>
<td>Power</td>
<td>42 W</td>
</tr>
<tr>
<td>Receiving Area</td>
<td>4.5 m²</td>
</tr>
<tr>
<td>Power-Aperture Product</td>
<td>206 W/m²</td>
</tr>
</tbody>
</table>

PMT Linearity
With the increased sensitivity of the new ALO Rayleigh Lidar, the high return signal causes PMT nonlinearity at lower altitudes, therefore, the photon counts below an altitude of approximately 60 km are undercounted, as expected.

We are currently applying a dead-time correction to the counting rate to account for this effect. In the future, we will employ additional detector channels for lower altitudes, as indicated in Figure 2. In the mean time, linearity testing was conducted, finding a dead time of 14 ms. The data was then corrected according to:

\[ N = \frac{M}{1 - \tau M} \]  

where \( N \) is the corrected number of photoelectron counts per second, \( M \) is the observed number of photoelectron counts per second, and \( \tau \) is the dead time. This effect is illustrated in Figure 4. The black line shows the observed counts in two minutes; the red line the corrected counts. In that figure, the correction is significant from 35 to 65 km. In addition, Figure 4 shows the chopper opening a little above 50 km, the PMT gate turning on at 30 km, and a cloud at about 1 km.

First Temperature Results
The original ALO Rayleigh lidar operated from 1993 to 2004, developing an extensive data set spanning 11 years. From that an 11-year temperature climatology was developed. The new system has begun to add to this data set. As predicted, the system is probing higher into the atmosphere, making it, so far, to nearly 105 km, this upper limit should increase even further.

Conclusion
Presented above are first observations from the new ALO Rayleigh lidar consisting of four collecting mirrors and two lasers, whose signals have been combined into one PMT detection channel. Having proved the feasibility and functionality of such a system to reach significantly higher altitudes, we will now proceed with additional detector channels that will be used to gather data from a larger altitude range than was previously possible by any other remote sensing system. Additionally, temporal and spatial resolution of the new system will allow for unprecedented measurements of phenomena throughout the middle atmosphere.

Acknowledgements
The construction of the very large lidar facility was made possible by funds from NSF, AFOSR and USU. We gratefully acknowledge support from the Rocky Mountain NASA Space Grant Consortium, the Howard G. Blood Graduate Scholarship program, the USU Physics Department, USU, and personal contributions to enable us to obtain the first data from this facility.

Figure 1. Two 532 nm laser beams in parallel shooting up through the atmosphere that hit the barreling mirrors, the addition of multiple larger mirrors and a second laser, the new system is substantially more sensitive in its raw data collection. This increased sensitivity enables data to be acquired to greater altitudes and analyzed with better resolutions and precision.

Figure 2. Current ALO Rayleigh lidar and planned upgrades. The increased sensitivity of the new system is evident in the raw data, seen as the average number of photoelectrons counted in two minutes. As can be seen in Figure 2, the new, large Rayleigh lidar detects, so far approximately 30 times more photoelectrons than the original configuration at an altitude of 60 km, which means that the new system is able to acquire data at higher altitudes than the predecessors. At approximately 60 km, the new system is able to gather significant data in two minutes whereas the old system has no perceivable count rate at this altitude.

Table 2. RML Lidar Altitude Ranges

<table>
<thead>
<tr>
<th>Altitude Range</th>
<th>High Rayleigh</th>
<th>Mid Rayleigh</th>
<th>Low Rayleigh</th>
<th>Mie</th>
</tr>
</thead>
<tbody>
<tr>
<td>65-115 km</td>
<td>45-90 km</td>
<td>15-65 km</td>
<td>3-45 km</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Temperature vs. altitude with all-night integrations for (a) 13 - 15 June 2012 with one laser and (b) 16 - 18 June 2012 with both lasers.

Figure 4. Effects of PMT nonlinearity on the return signal. The plot illustrates, as the PMT goes non-linear at lower altitudes, the MCS unit undercounts the photoelectrons by 30 times. The red line shows the corrected counts. In that figure, the correction is significant from 35 to 65 km. In addition, Figure 4 shows the chopper opening a little above 50 km, the PMT gate turning on at 30 km, and a cloud at about 1 km.

Figure 5. Effects of PMT nonlinearity on the return signal. The plot illustrates, as the PMT goes non-linear at lower altitudes, the MCS unit undercounts the photoelectrons by 30 times. The red line shows the corrected counts. In that figure, the correction is significant from 35 to 65 km. In addition, Figure 4 shows the chopper opening a little above 50 km, the PMT gate turning on at 30 km, and a cloud at about 1 km.

Figure 6. AGW structures such as vertical wavelength and phase velocity appear in relative density perturbation profiles. This analysis from the original lidar’s data set will be extended with the new data. With the increased sensitivity, a greater altitude range can be examined along with parts of the spectrum with shorter periods (less than an hour), and smaller vertical wavelengths, (less than 6 km). Of particular interest will be the analysis of gravity wave studies upward from the simplicity of much of the mesosphere into the more complex mesopause.

Figure 7. Relative density perturbation profiles from 6 January 1995. Each profile is offset by one hour and the horizontal axis gives +/-10% density fluctuation from central dashed vertical line. The bars containing green dots give a sample of horizontal phase velocities (Kafle 2009).

Improved Atmospheric Gravity Wave Studies
Another important study that will benefit from the increased sensitivity of the new, very large Rayleigh system is that of atmospheric gravity waves (AGWs). Like the temperature climatology, AGW studies were carried out with data taken using the original Rayleigh lidar, having first been explored by Kafle (2009).

From the raw data, relative density perturbations in temperature and relative humidity perturbations in temperature are analyzed to show AGW activity. As can be seen in Figure 6, AGW structures such as vertical wavelength and phase velocity appear in relative density perturbation profiles. This analysis from the original lidar’s data set will be extended with the new data. With the increased sensitivity, a greater altitude range can be examined along with parts of the spectrum with shorter periods (less than an hour), and smaller vertical wavelengths, (less than 6 km). Of particular interest will be the analysis of gravity wave studies upward from the simplicity of much of the mesosphere into the more complex mesopause.

Additional Future Work
Along with continuing optimization of the lidar’s various systems, there will be further upgrades as well. As can be seen in Figure 2, three more PMT detection channels (the pale PMTs) will be added to the system. One of these channels will be for containing Rayleigh scatter measurements down to approximately 40 km (the original lidar’s lower limit), another channel will measure both Rayleigh and Mie scatter from 15-65 km and the final channel will measure Raman scatter from 15-45 km (Table 2). The rate at which this will occur and the examination of scientific problems with this unique system will depend on significant future funding.