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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 operate at 532 nm. This wavelength was chosen to take advantage of the first-order Rayleigh scattering. Light backscattered from the rayleigh scattered across polarizers. Photons emitted from the laser are backscattered in the middle atmosphere and collected by four 1.25 m diameter parabolic mirrors, equivalent to one 2.5 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.

Figure 1. Two 532 nm laser beams in parallel shooting up through the stratosphere that holds the four receiving 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.

This first observations with this system will be recently acquired, on June 13, 2012. The first temperature profiles are presented in the next section to illustrate this improved capability. Future studies of atmospheric gravity waves and other middle atmosphere phenomena will benefit from these improvements.

Raw Data Comparison
The increased sensitivity of the new system is evident in the raw data, as seen in the average number of photoelectrons collected in two minutes. In Figure 3 (a) and (b), the photoelectron counts are represented as “counts” and are plotted versus altitude. As can be seen in the figures, 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 old system. At approximately 90 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.

Figure 2. Current ALO Rayleigh lidar and planned upgrade. The increased sensitivity of the new system is evident in the raw data, as seen in the average number of photoelectrons collected in two minutes. In Figure 3 (a) and (b), the photoelectron counts are represented as “counts” and are plotted versus altitude. As can be seen in the figures, 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 old system. At approximately 90 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.

First Temperature Results
The original ALO Rayleigh lidar operated from 1993 to 2004, developing an extensive data set spanning 14 years. From that an 11-year temperature climatology was developed. The new system has begun to add to this data set, with additional periods of profiling. As can be seen in the figures, the new lidar system’s data show that the system is able to gather significant data at a greater 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.

Figure 4. Effects of PMT nonlinearity on the return signal. The plot shows a time series of observed PMT nonlinearity counts corrected and uncorrected. Each time series is offset, so the black line shows the observed counts in two minutes; the red line the corrected counts. In this 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. Temperature vs altitude with all-sky integrations for (a) 15 June 2012 with one laser and (b) 16 June 2012 with both lasers. Figures 5(a) and (b) show the first two temperature profiles observed near the summer solstice. The recorded temperatures near the mesopause approach the conditions that are needed for the formation of noctilucent clouds (NLCs), such as those previously observed by the ALO Rayleigh group. NLCs form high at altitudes (<8-8.5 km) and usually above 30° latitude. Observers are currently taking data with the system every clear night with the goal of making additional NLC observations.

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 systems. 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, AFSOR, and USU. We gratefully acknowledge support from the Rocky Mountain NASA Space Grant Consortium, the Howard J. Blood Graduate Scholarship program, the USU Physics Department, USU, and personal contributions to enable us to obtain the first data from this facility.

Improved Atmospheric Gravity Wave Studies
Another important study that will benefit from the increased sensitivity of the new, very large Rayleigh lidar 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 perturbations can be 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 one hour), and smaller vertical wavelengths, (less than 6 km). Of particular interest will be the use of the new system to improve gravity wave studies upward from the simplicity of much of the mesosphere into the more complex mesopause.

Figure 6. Relative density perturbation profiles from 4 January 1995. Each profile is offset by one hour and the horizontal axis gives ±10% density fluctuation from central dashed vertical line. The dots connecting the data points give a visual sense of horizontal phase velocities (Kafle 2009)

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, there are three PMT detection channels (the pale PMTs) that will be added to the system. One of these channels will be dedicated to 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 role of this new system will be to carry out the examination of scientific problems with this unique system will depend on significant future funding.

Table 1. ALO Rayleigh Lidar Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<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>4.8 m²</td>
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<tr>
<td>Power-Aperture Product</td>
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Table 2. RMI Lidar Altitude Ranges

<table>
<thead>
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<th>Altitude Ranges</th>
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<th>Mid Rayleigh</th>
<th>Low Rayleigh</th>
<th>Raman</th>
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<td>45-115 km</td>
<td>40-99 km</td>
<td>15-65 km</td>
<td>15-45 km</td>
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</tbody>
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