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## Lidar User's Manual

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# **LIDAR USER'S MANUAL**

by

**Lance William Petersen**

**Thesis submitted in partial fulfillment  
of the requirements for the degree**

of

**DEPARTMENTAL HONORS**

in

**Physics  
in the Department of Physics**

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**Logan, UT**

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# Lidar User's Manual

## 1. Introduction

This is intended to be a user's manual for the upgraded USU Rayleigh lidar. As such, it begins with a discussion of the purpose of a lidar. This is followed by a brief explanation of the fundamentals of Rayleigh scatter lidar. Next the reasons for and benefits of upgrading the lidar are discussed and as well as how the upgrade was accomplished. After establishing this basis, instructions are provided for operating the lidar, performing basic maintenance, and aligning various components.

The atmosphere is complex and constantly varying system, but in a general way it is possible to divide it into layers or spherical shells. These layers are determined by their various chemical, dynamical, or thermal structure. As determined by the neutral temperature structure, going up from the surface these layers are the troposphere, stratosphere, mesosphere, and thermosphere.

Due to the conditions in the middle atmosphere, which corresponds to the stratosphere and mesosphere, it is difficult to obtain measurements in this region. The lower atmosphere is measured twice daily by radiosondes carried by balloons up to about 30 km and the upper atmosphere is routinely measured by satellites. The region between 80 and 100 km can be measured optically using airglow emissions or with several types of radars. This leaves a gap between about 30 and almost 80 km where measurements are difficult to make. A Rayleigh-scatter lidar is able to measure atmospheric densities and temperatures continuously in this range (*Beissner, 1997*).

## 2. Lidar Theory

Lidar stands for Light Detection and Ranging. A laser is used to shine a collimated beam of photons with a specific wavelength up into the atmosphere. As the photons travel upward, some of them scatter elastically off the molecules in the atmosphere. This process is known as Rayleigh scattering and occurs when the objects causing the scattering (e.g. N<sub>2</sub> and O<sub>2</sub>) are much smaller than the wavelength of the laser. The angle at which these photons are scattered varies, but some of them will be directed back downwards. These back-scattered photons are then collected by mirrors and carried via optical fibers to the lab below where they are detected using a combination of optical elements and one or more photomultiplier tubes (PMTs).

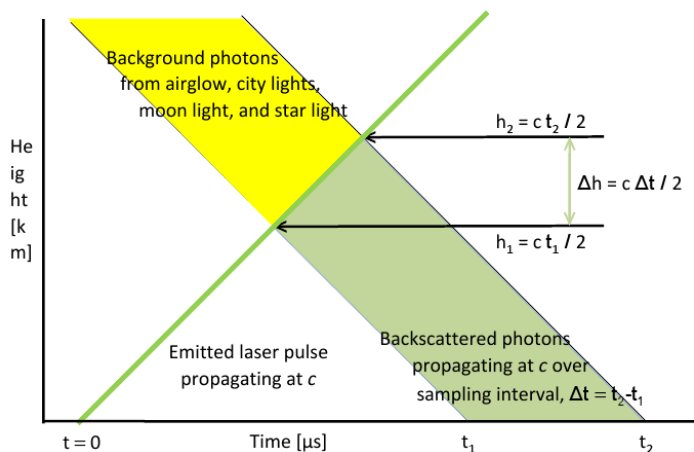
One of the most important components of this system is the Nd:YAG laser. It is known from quantum mechanics that energy is quantized and there are only specific allowed energy levels in matter. A laser takes advantage of this quantization of energy. Within our laser there are four chambers, each in the shape of an ellipsoid with a flash lamp at one locus and a rod of lasing material at the other. When the flash lamp is fired, photons of many wavelengths are emitted and the elliptical shape ensures that all of the photons strike the rod. The quantized nature of energy allows us to only excite the electrons to the desired energy level. Under normal circumstances, these excited electrons would spontaneously de-excite and each would emit a photon at the same wavelength. This would lead to a longer pulse than we desire, so we employ a Q-switch mechanism that allows a large population of excited particles to build up and then stimulate them to emit in a short time. This results in a pulse width of ~8 ns (*Beissner, 1997*).

To get the largest returns from the atmosphere, we take advantage of the Rayleigh scattering cross section having a  $\lambda^{-4}$  dependence on wavelength. This means that as we decrease  $\lambda$ , we get greater returns. The Nd: YAG lasing material results in an output beam with a

wavelength of 1064 nm, which is in the infrared. By placing a specific crystal in the optical path, the beam can excite harmonic oscillations which can double or even triple the frequency, decreasing the wavelength by a factor of two or three respectively. This tripling seems like it would be the best option, but other factors, such as atmospheric transmittance, optical transmission, energy per laser pulse, and conversion efficiency, make it so that the doubling is better for our purposes. It also has the advantage that the beam is visible. Doubling the frequency decreases the energy by 50%, but cutting the wavelength in half makes the return signal 16 times bigger, so even with the energy loss the process results in an improvement of 8 times (*Herron, 2004*).

The actual measurements that we make are time and photon counts. We know at what time the pulse was sent and we detect when a photon returns and hits the detector. We know that the speed of light is a constant, so we can tell how far the photon was able to travel  $d = c * t$ . Since we know that the photon went up and then came back down to our detector, we know that the height is  $h = d/2 = (c * t)/2$ . By grouping the photon counts into manageable bins of time, it is

## Lidar—Light Detection and Ranging



possible to say that  $x$  photons returned from a region of atmosphere  $\Delta h$  thick. We know that the number of photons that experience scattering is dependent on the density of the atmosphere in that region. More dense regions of atmosphere will

scatter more photons and regions of lower density will scatter fewer. Thus, a high return from a region of atmosphere corresponds to high density.

Our observations start at the ground but due to Mie scattering at low altitudes, the density profiles do not start until ~25 km. One source of this type of scattering is thin cirrus clouds, which can vary on the scale of 10 minutes. Another source is the dust and other particulates and aerosols in the air. Analyzing the data from a region with Mie scatter is a different process that is not part of the current system. Since we do not know the actual density at the altitude where we begin analyzing the data, the results can only be relative densities. It is possible to tell how much more dense one region is than another, but not to determine the absolute density. The short time scale variations of the cirrus clouds also make it impossible to compare the relative density profile at hour 1 with the relative density profile at hour 5. This is because the clouds attenuate the signal and can change rapidly.

### **3. Purpose of Upgrade**

A measure of the sensitivity of a lidar is its Power-Aperture Product (PAP). This is the product of the power of the laser and the area of the collecting mirrors. In the old system an 18 W laser was used along with a 44 cm diameter mirror, with a small area missing because of the secondary reflector on the Newtonian telescope. The Power-Aperture Product of this system was  $2.7 \text{ Wm}^2$  and it was able to make measurements up to approximately 90 km. In the upgraded system a 24 W laser is used and 4 mirrors, each with a 1.25m diameter. This system has a PAP of  $117 \text{ Wm}^2$ . In the near future, we plan to add the 18 W laser from the old system to the new, which will give a final PAP of  $205 \text{ Wm}^2$ .

The benefits of having a higher Power-Aperture Product are improvements in height, time resolution, spatial resolution, and precision. With the new system it will be possible to measure up to approximately 110 km with the same precision and resolution as the old system. This is higher than any other Rayleigh lidar is able to measure.

Alternatively, it is possible to improve the time resolution from hours down to minutes. Since the Power-Aperture Product is 70 times greater than it was, where 1 hour was required in the old system, only 1 minute would be needed with the fully upgraded system. This is only true if we measure to the same heights as the previous system with the same precision and spatial resolution. This increase in resolution would allow measurements of features that are changing more rapidly than we were previously able to detect.

It is possible to increase the spatial, or altitude, resolution instead. If the altitude, precision, and integration times from the old system are used, a spatial resolution of 37.5 meters can be achieved. This would allow a much closer examination of gravity waves with small wavelengths. This is also useful for measuring thin layers, such as noctilucent clouds, cirrus clouds, and as yet unidentified layers that have been seen in the mesosphere stratosphere that are about 1 km thick.

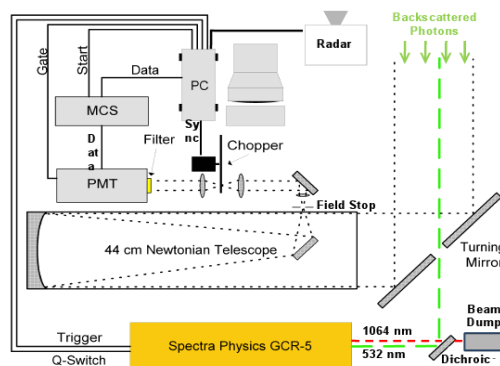
Another option is to decrease the uncertainties in measurements taken with all of the other factors remaining constant. Although I have discussed each of these four features separately and as though all of the others remain constant while improving one, it is possible to do any combination of the four. Doing such a combination would yield better results in each, but not to the same extent as improving just one at a time.

A very important feature of these improvements is that all of them are contained in each set of data. When a night of data is collected it can be analyzed one way to increase the precision. These results can then be compared directly to those obtained by the old system, but with much smaller uncertainties. Then the exact same set of data can be re-analyzed, this time leaving the precision at the same level as the old system and improving the spatial resolution instead. This process can be repeated with each type of improvement. This is because the upgrade improves the quality of the measurement itself and the analysis determines how that improvement is manifested, but the analysis does not change the data. Thus, the data can be re-analyzed for each type of improvement or combinations of them.

#### 4. Upgrade

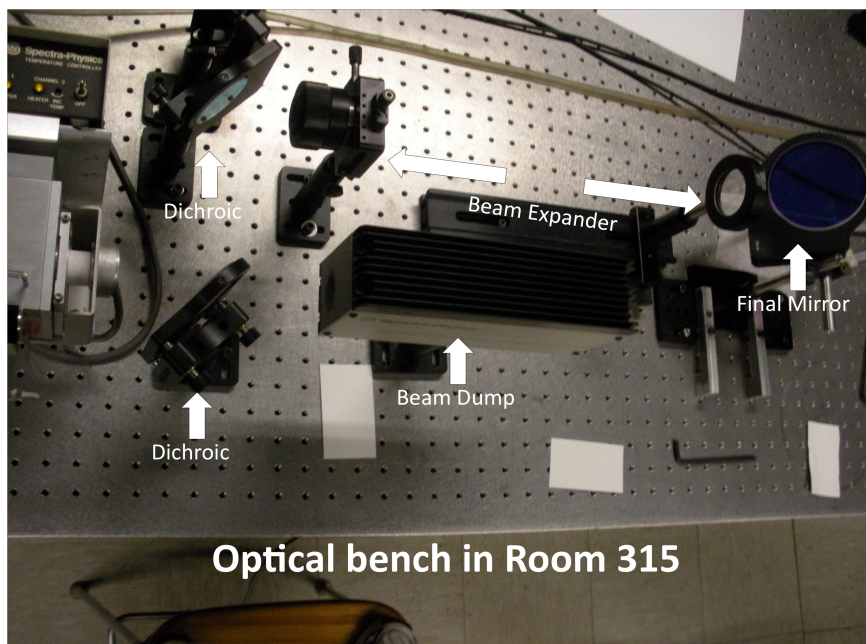
In the old system two dichroics were used to separate the 532 nm laser emission from the original 1064 emission and to reflect the resultant 532 nm beam upwards. A dichroic is an optical component that allows the remainder of the 1064 nm light to pass through it to beam dumps behind them, while reflecting the new 532 nm light. Then a single 44 cm diameter mirror was used as the primary mirror in the Newtonian collecting telescope.

#### Block Diagram of Lidar System



Adapted from Herron [2004]

In the new system, the beam is sent through 2 dichroics. Next we send it through a beam expander and then it hits one final mirror to aim it into the sky. The next step is the lidar receiver, which collects the return signal from the sky and sends it to the detector. We have a large



structure on the roof of the SER building that houses four parabolic mirrors, each one with a 1.25 m diameter, giving the whole the equivalent of a 2.5 m telescope. Held at the focal length, directly above each mirror is one end of an optical fiber. When photons

from the beam scatter in the atmosphere, some of them will be directed back downwards and these mirrors collect those photons, which are then reflected to the focal point where they enter the optical fiber and are transmitted down into the lab below. The fiber is 1.5 mm in diameter and has a numerical aperture (N.A.) of 0.39. Each mirror forms an image of the illuminated spot in the sky that is about 0.75 mm in diameter.

The cage structure which holds the 4 mirrors

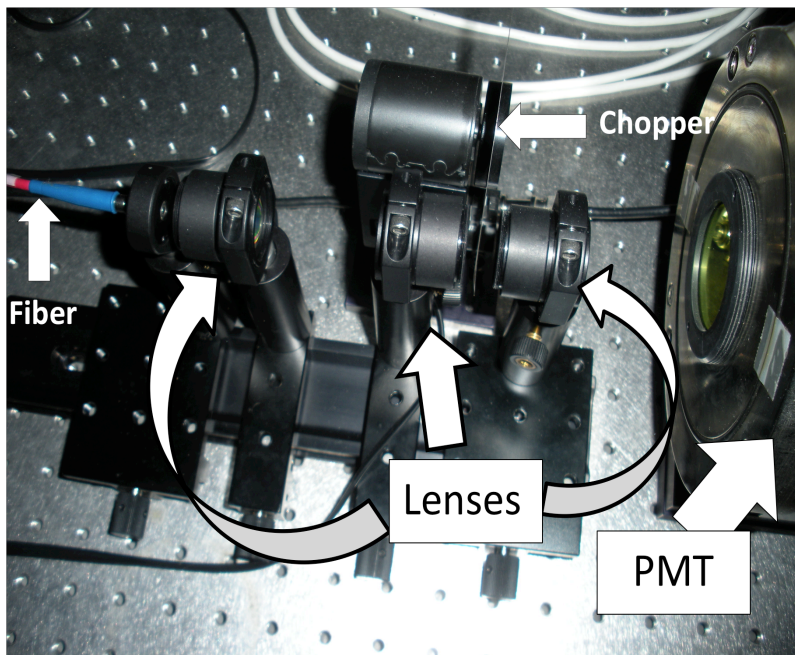


A close up of the fiber holders





In front of the lab end of the fiber is a lens to collect the entire return signal and collimate the beam. This is an  $f/1.2$  lens to match the N.A. of the fiber. A second identical lens is used to



focus the beam to a small spot in the plane of a mechanical chopper. This chopper is a wheel with 2 slots cut into it which spins at a specific frequency (105 Hz, which with the two openings, generates a 210 Hz signal) and is used to physically block the light from

the lowest altitudes. This is done because the low altitude light would be so bright that it might damage the photomultiplier tube (PMT) detector. On the other side of the chopper is a third identical lens that once again collects and collimates the light so that it can be sent into an interference filter and then the PMT. The interference filter is 1 nm wide and has peak transmittance of 80% at 532 nm. For the filter to work properly, the incident light has to be collimated and perpendicular to the surface. This filters out extraneous light from airglow, stars, moon, and scattered city lights. There are few photons that eventually reach the detector, which is why a PMT is used. The PMT has a photocathode with a quantum efficiency of about 15%. The ejected photoelectrons are accelerated to a dynode where each one knocks off two or three electrons. With 12 such dynodes, the PMT multiplies the initial signal by approximately  $10^6$ .

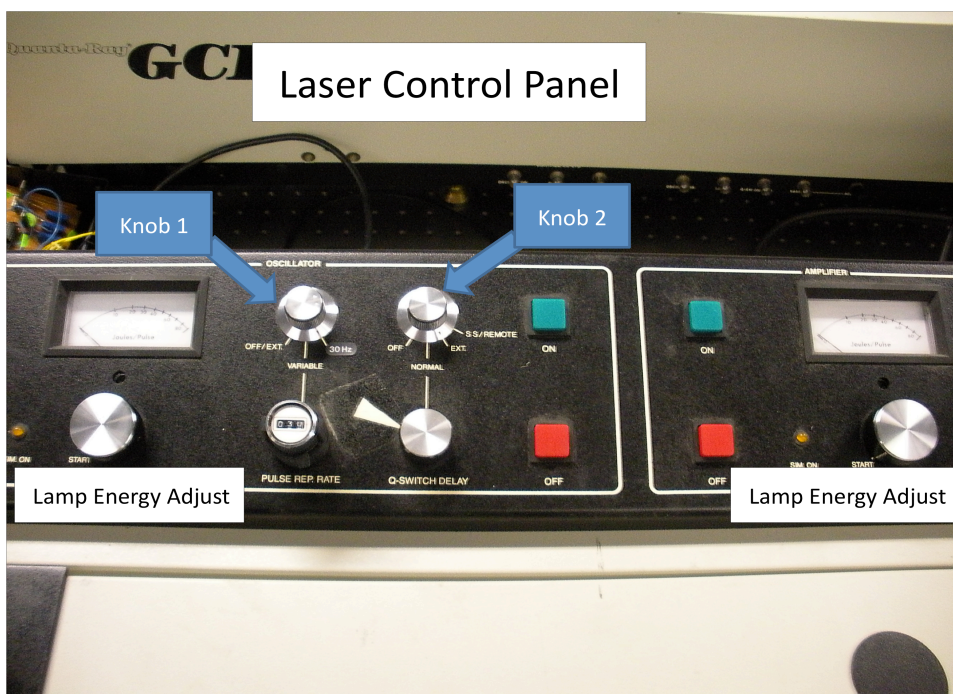


Thus, this detector converts a very small signal to one that is measurable by other electronic devices and can then be analyzed.

Another very important part of this system is the timing program. It is important that all of these components work together with very precise timing. It is controlled by a LabVIEW program which was restructured from the program that ran the previous lidar system. The basis of the timing in this set-up is the mechanical chopper that is used to block the signal from the lowest altitudes. The 210 Hz output from this chopper is sent into the timing program where it is divided by 7 to produce a 30 Hz signal. This then has an arbitrary delay of 1.5 milliseconds (ms) followed by another delay of approximately 2.0 ms before sending the signal to fire the flash lamps in the lasers. Varying this 2.0 ms delay controls the altitude at which the chopper lets the return signal pass through the system. This same 30 Hz signal is sent to another channel, delayed an additional 270 microseconds, and sent to trigger the Q-switch and the data acquisition unit. This Q-switch delay is introduced so that the flash lamps will have enough time to create a population inversion in the optical cavity before sending the pulse that actually triggers the laser to fire. The signal being sent to the Q-switch is also sent to the data acquisition unit, the multi-channel scaler (MCS), which causes time 0 to correspond to the firing of the laser. This is how the firing of the laser is synchronized with the timing to determine the range (or altitude) that the photons are returning from. A separate channel in the timing card receives the signal going to the Q-switch and delays that signal an additional 250 microseconds, corresponding to 37.5 km, before sending it to the PMT to gate it on. Initially the PMT gain is as small as we can make it, again to protect from the large low altitude signals. When close to the altitude at which we want to make measurements, the PMT is gated on.

## 5. How to Operate

Laser: The first thing that should be done when beginning is to start warming up the laser. This process takes the longest amount of time and is fairly simple. First, make sure that no BNC cables are connected to the laser. Now turn on the water in the lab in Room 315. This provides the water to cool the laser. Then make sure the key is turned to the on position and flip the “oscillator” and “amplifier” switches on the laser power supply. Now push and hold the green



buttons on the top panel of the laser labeled “ON”. These buttons need to be held down for a couple of seconds and then can be released. If the light turns off

when the button is released, push again and hold them down longer. This causes the flash lamps to simmer and begins warming up the laser. The “SIM. ON” lights should turn on during this step. There are several interlocks on the laser. These are mechanisms that will automatically turn the laser off under certain conditions. One of these is for water pressure, which prevents the laser from running if there is not sufficient water pressure to cool it. There is another interlock to make sure that the cover is on the laser.

After allowing the lamps to simmer for a few minutes, the flash lamps need to be turned on. This is done by turning the knob labeled Knob 1 in the figure labeled Laser Control Panel to the 30 Hz position and Knob 2 to the EXT position. This will allow the flash lamps to fire at the 30 Hz rate that is set by the laser, without any Q-switching occurring. Now turn the laser on by slowly turn the Lamp Energy Adjust knob on the left side of the laser up to its maximum setting. This should take at least 4 seconds. Follow the same procedure with the Lamp Energy Adjust knob on the right side of the laser. The laser should be run for approximately 10 minutes on this setting. This is a convenient time to perform some of the other starting procedures.

After the flash lamps have warmed up, it is time to put the laser on long pulse. This is done by slowly turning the Lamp Energy Adjust knobs down to zero one at a time. Then change the setting on Knob 2 from EXT to OFF and turn the power back up. Once again, allow the laser to run on this setting for approximately 10 minutes. This is the setting that should be used to align optics on the table before sending the beam into the sky and the initial check for the verticality of the beam. This is another good time to move on to other start up procedures.

Next is to turn the laser to short pulse. This is the setting that is used to take data. Once again, turn the power off slowly. Now turn Knob 1 to OFF/EXT and turn Knob 2 to EXT. This allows the flash lamps and the Q-switch to be controlled by the timing program. At this point connect the BNC cable labeled flash lamp to the connector on the front of the laser under the Control Inputs labeled LAMP and the BNC



labeled Q-switch to the Q-SW (IN/OUT) under the Sync Outputs. The power Lamp Energy Adjust knobs can now be slowly raised back to their maximums. This will cause the Q-switching to operate normally and results in the shorter pulse and the strongest signal. At this point, the laser is ready for normal data acquisition. If it is necessary to run the laser without being controlled by the timing program, simply leave Knob 1 on 30 Hz and move Knob 2 to “Normal” while leaving the BNCs disconnected.

Mirrors: While the laser is warming up is a good time to go up to the roof and prepare the mirrors. First, check the weather and if it is good, open the roof. Next, remove the wood panels that are covering each of the mirrors, if work is being done on the system. Now remove the black PVC board coverings from the mirrors which are always there when the telescope is not in use. This is best done with one person standing on the ground and reaching in to get the board, while the other person stands on the cage in between two mirrors and helps lift up before pulling the board out. This needs to be done carefully so as to avoid scratching the mirrors.

Alignment: There are many places which require aligning in this system. It is important that the laser beam is aligned properly on the optical table because this is an area where people will be working and it could cause damage. One of the reasons for using a wavelength of 532 nm is so that it will be visible and allow for easier alignment. The beam needs to go through both dichroics, then the beam expander, and finally hit the final mirror. It is important that along this path, the beam is not being clipped by any components. Alignment is accomplished by rotating the dichroics and moving the components on the table.

It is also important that the laser be shining vertically. The initial alignment is accomplished by using two wooden disks, each of which has a hole in the center. One of these is

placed over the center hole in the floor of the lidar observatory on the roof, directly below the cage. The other is placed over the hole in the center at the top of the cage. The laser is then turned on and set to long pulse. Now adjust the final mirror downstairs until the beam is shining through the hole in the center of the first wooden disk. One person can lie down on the wooden coverings over the mirror and watch where the beam strikes the second wooden disk. If it is hitting to the north and east of the center, then the optical table with the laser needs to be lifted onto the wheels and moved north and east. At that point, the table is lowered and the final mirror is adjusted until the beam shines through the first wooden disk. This process is repeated until the beam goes through the center of the second disk. After this initial alignment, the verticality of the laser beam is checked by walking around campus and comparing it to the edges of some of the buildings. The library and the engineering buildings provide good reference buildings. An important feature of the stepper motors that control the final mirror is that they are on a closed loop. That means that taking 100 steps one direction and then taking 100 steps back will leave you in the same place you started. This is not true of all stepper motors, but it is a very useful thing to be sure that you are in the same place you started.

Once the laser is vertical, the four large mirrors need to be aligned. The fastest check can be done by holding a sheet of white paper just under the fiber holder. Enough light is reflected from the lowest altitudes that it forms a visible spot very close to the focal point. The three bolts on the bottom of the mirror supports can be adjusted until the spot is centered on the end of the fiber.

This spot will show where the focus is for the lower altitudes, but for the region we are measuring the focus will be slightly higher than that. After this rough calibration has been done, the finer measurements and adjustments can be made by tilting the laser and taking

measurements. Using the stepper motors, the beam can be tilted 100-200 steps (100-200  $\mu\text{rad}$ ) in one direction and the return recorded. Then move the mirror back to the center and then 100-200 steps in another direction. Doing this systematically and keeping track of the count rates at a specific altitude, a map of the maximum signal can be made. If this is too wide, then the fiber is currently too high or too low and should be adjusted to maximize the signal and minimize the area of high returns.

The next step is to make sure that the optical path in front of the PMT is aligned. Currently, one fiber is mounted in the box in room 315 with a lens after it to collect the cone of light coming from the fiber. This first lens collimates the beam and shortly after it is a second lens to focus the beam to a point. The optical chopper is placed so that it chops the beam at the smallest diameter, so that it will be able to chop it in the shortest time. Then a third lens is used to collimate the beam again before sending it into the PMT, which has an interference filter on the front. This interference filter blocks light that is not 532 nm and it has a 1 nm width.

Timing Program: Operating the timing program is quite simple. After the chopper has been turned on and allowed to warm up, all it requires is opening the timing program (Lidar Timing.vi) and pushing the “run” button in LabVIEW. The front panel of this program allows the user to set the delay time and pulse width of various signals that are controlled by the timing card. This allows the user to make adjustments as they become necessary.

Data Acquisition: The MCS is the main piece of equipment for the data acquisition. My fellow student has written a program that will allow a user to make a file to record extended data sets. Thus far we have only used short sets of data. This is sufficient to align the components and get preliminary results. The MCS has a buffer that will store these short sets. In the MCS program it

is possible to set the pass length, dwell time, and pass count. The dwell time determines the length of time that is binned together and therefore the thickness, or  $\Delta h$ , of the slice of atmosphere that is measured. The pass length determines how many of these slices are recorded and therefore the maximum height that the returns will be recorded from. The pass count determines the integration time or how many pulses of the laser will be integrated over to obtain the density profiles.

## 6. Future Work

Due to difficulties with the weather and some equipment, we have not been able to obtain any useable data with the new system. However, we have been able to turn on the laser and see a return signal from the sky. Thus we have obtained first light on the system. This is encouraging and helps verify that the system is moving speedily towards a successful completion. It is planned that it will be functioning for a campaign to observe noctilucent clouds beginning in June.

Once the new system is working there are many different topics that can be studied with this technique. The following topics are based on what has been observed in the earlier data set and what people expect to see at mid latitudes. These topics include:

- Temperature trends (climate variation)
- Response to solar cycle variations (e.g., to F10.7 and other proxies)
- Interannual temperature variability (what are the causes?)
- Quasi-biennial oscillation (is it detectable at this latitude?)
- Annual, semi-annual, and higher order temperature variability (origin of asymmetry and higher order terms)

- Day-to-day variability (temperatures and gravity-wave energy)
- Gravity waves (spectrum, sources, energy and its deposition)
- Thermal tides (periods, amplitudes, and phase progression with altitude)
- Planetary waves (relation to mesospheric inversion layers)
- Episodic events (e.g., volcanic eruptions affecting temperatures)
- Density variations in the lower thermosphere (space weather)
- Two-level mesopause (conditions affecting this sudden summer-winter change)
- Noctilucent clouds (conditions under which they occur)
- Very large-amplitude temperature waves near 80 km
- Stratopause altitude and its variability
- Sudden stratospheric warmings (and mesospheric coolings)
- Thin (~1 km) descending layers in the mesosphere and stratosphere
- Very cold temperatures in January in the lower mesosphere
- Isolated cold region in early October between 80 and 87 km

Another exciting thing that will be done with the lidar is to make comparisons with another technique that makes comparable measurements at an altitude that overlaps where this system measures. In summer 2010 a sodium lidar system was moved here from Colorado State University. This system measures temperatures, winds, and sodium densities between approximately 82 and 103 km. This lidar scatters off sodium atoms in a layer found in the atmosphere, created by the disintegration of micrometeorites, centered at approximately 92 km. This sodium lidar is located in the same lidar observatory on the roof of the SER building. This provides a great opportunity to have both instruments take measurements simultaneously from the same location. This will be the first time that a comparison of this kind will have occurred. It is a wonderful opportunity to check how well these two different techniques agree. Both lidars claim to be able to make temperature measurements, but they are based on very different



physical principles. If it is found that they agree, it will validate the confidence that we can have in these methods. However, if they do not agree then it will be important to find the cause of the disagreement so that better models and measurements can be made.

We are in the process of adding a second laser to the current arrangement. The second laser has already been relocated to room 315 and placed on the optical bench. To integrate this laser into the lidar it is necessary to use 2 additional dichroics with beam dumps behind them, a beam expander, and an additional channel in the timing card and program. It will be necessary to align this beam so that it will hit the final mirror next to the first laser, without interfering with the first laser. The timing will need to be such that both of the lasers Q-switch at the same time, causing their pulses to fire simultaneously. It is unlikely that the second laser will have exactly the same delay between the flash lamps and the Q-switch, so a new channel will need to be wired in the timing card and a corresponding channel has been added to the program to cause the flash lamps of the second laser to fire. The signal to Q-switch the first laser will then be split so that it will also trigger the Q-switch on the second laser, as well as the MCS unit.

Extending the range of the measurements to lower altitudes is also planned for the future. This can be accomplished by splitting the original signal in the data acquisition box so that a large percentage of the backscattered light goes into the highest altitude PMT and the rest is diverted onward. By only allowing a small percentage through, it decreases the signal from the lowest altitudes enough that it will not harm the PMT. This PMT can then detect signals from the lowest altitudes. Due to the fact that only a small percentage of the original signal is needed for that, most of the signal is still available for reaching higher altitudes. This process can be repeated to reach middle altitudes. Obviously doing this requires multiple functioning choppers

and PMTs, one for each altitude range. With three detectors in place, the goal is to cover the altitude range between 25 and 110 km.

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