REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-04-

0100

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
	Final Report	Apr 1, 01 - Sep 30, 02

4. TITLE AND SUBTITLE
Lidar Upgrade for Temerature, Winds, and Structures at the Edge of Space

5a. CONTRACT NUMBER

5b. GRANT NUMBER
F49620-01-1-0275

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Dr. Vincent B. Wickwar

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Utah State University
Center for Atmospheric and Space Sciences

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of the Air Force 4015 Wilson Blvd.
Air Force Office of Scientific Research Arlington, VA 22203-1954

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release. Distribution unlimited

20040220 314

13. SUPPLEMENTARY NOTES
DODAAD CODE: 4B969
AFOSR Program Manager: Major Paul Bellaire

14. ABSTRACT
With funds from DURIP grant 1249620-01-1-0275, Utah State University (USU) purchased equipment and components to upgrade the Atmospheric Lidar Observatory (ALO) operated by the Center for Atmospheric and Space Sciences (CASS) on the University campus. (Other funds are being used for labor to integrate these into the lidar system.) The upgrade is to the large lidar telescope and to related laser and detector systems. 'Ibis will make it possible to measure Doppler winds and spatial structures in neutral density' anti temperature at the edge of space (i.e., in the upper mesosphere, mesopause, and lower thermosphere) between 80 and 105 km altitude. This is a region that has been very difficult to study front the ground or from space. Yet it is a region with very strong winds, waves, and variability in temperatures and densities. This upgraded research capability at Alt will provide a long-term ability at mid latitude to specify this region and to determine the dominant physics so as to develop a predictive capability. This includes distinguishing the effects of space weather from those that propagate upwards into this region. The information garnered by this research will be applicable to numerous Air Force (AF) programs and systems including those that need to evaluate infrared backgrounds and distinguish man-made objects from structured backgrounds, that are affected by large time-varying density

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Vincent B. Wickwar
					19b. TELEPHONE NUMBER (Include area code)

Final Report for DURIP Grant F49620-01-1-0275

Vincent B. Wickwar
Utah State University
Center for Atmospheric and Space Sciences

LIDAR UPGRADE FOR TEMPERATURES, WINDS, AND STRUCTURES AT THE EDGE OF SPACE

Abstract. With funds from DURIP grant F49620-01-1-0275, Utah State University (USU) purchased equipment and components to upgrade the Atmospheric Lidar Observatory (ALO) operated by the Center for Atmospheric and Space Sciences (CASS) on the University campus. (Other funds are being used for labor to integrate these into the lidar system.) The upgrade is to the large lidar telescope and to related laser and detector systems. This will make it possible to measure Doppler winds and spatial structures in neutral density and temperature at the edge of space (i.e., in the upper mesosphere, mesopause, and lower thermosphere) between 80 and 105 km altitude. This is a region that has been very difficult to study from the ground or from space. Yet it is a region with very strong winds, waves, and variability in temperatures and densities. This upgraded research capability at ALO will provide a long-term ability at mid latitude to specify this region and to determine the dominant physics so as to develop a predictive capability. This includes distinguishing the effects of space weather from those that propagate upwards into this region. The information garnered by this research will be applicable to numerous Air Force (AF) programs and systems including those that need to evaluate infrared backgrounds and distinguish man-made objects from structured backgrounds, that are affected by large time-varying density changes, and that depend on thermospheric densities to determine ionospheric densities and their variations. These upgraded observational capabilities will complement and extend similar ones that the AF has supported at much higher latitudes (ALOMAR in Norway) and is supporting at much lower latitudes (AEGIS in Hawaii). This upgraded facility will significantly improve research opportunities at USU at all levels. ALO attracts many very good students. A half dozen undergraduate students carry out the observations and many of them participate in the research. Physics students use the facility and the data for their senior projects, presenting their results at local and national meetings. There have been two PhDs (an AF officer and a student from another university). Currently, there are two MS and one PhD students. With this upgrade, USU will be able to offer greatly improved educational opportunities.

1. INTRODUCTION

This DURIP grant (F49620-01-1-0275 for $198,352) has enabled USU to greatly improve the capability of two lidar systems at the Atmospheric Lidar Observatory (ALO), Utah State University (USU), to observe the edge of space, the region between 80 and 105 km. This region, which includes the upper mesosphere, the mesopause, and the lower thermosphere is on the one hand poorly understood, while on the other hand is highly variable and very interesting scientifically. This region, being at the edge of space and being highly variable, is important for its potential impact on Air Force (AF) systems. These impacts arise from the structuring in the region itself and the impact this structure has on the thermosphere and ionosphere above. It is important to specify the nature of this region and to develop a physical understanding of the region to make physics-based models of it in the future.

The next section, Section 2, discusses the research interests in this region and relates them to AF needs, and indicates the significant value of having observations at mid latitude, in between those at high and low latitudes. Section 3 describes the purchases made with this grant. Section 4 relates the capabilities of the improved ALO system to those of other lidar systems that probe this region, including ALOMAR (at high latitude) and AEGIS (at low latitude). Section 5 discusses the significant impact ALO has on education and how the improvements increase this impact. Section 6 gives the references.

2. RESEARCH ABOUT THE EDGE OF SPACE

The edge of space is a region with non-linear or turbulent mixing of constituents as well as large spatial and temporal variations. In keeping with this, the physics is dominated by dynamics instead of radiation. Observationally, it is a region that is only now yielding to investigation. While the broad outlines of what is happening in this region are known, the region is not well specified and much has to be done to gain a good physical understanding of the region that will eventually lead to physics-based predictive models.

This region impacts on AF systems in a number of ways. Any object that goes into space or descends from space passes through this region. The Space Shuttle has encountered considerable buffeting, the Space Maneuver Vehicle would be similarly affected, and the trajectory and accuracy of warheads can be changed. The structure in density, temperature, and constituents can lead to structure in the IR backgrounds that would be seen from space. The densities and temperatures in this region also become the bottom boundary condition for models of the thermosphere, which become important for the orbital decay and reentry of any vehicle that is in a low altitude orbit or has part of its orbit at low altitudes. These thermospheric densities also greatly affect the ionospheric densities and their variations, which in turn affect many communication systems. Information on this variable bottom boundary is particularly important during major space-weather events when it may be changing faster than can be inferred by such means as satellite drag.

However, this region cannot be understood in isolation. While some of the forcing functions and variability will arise from space-weather effects, others will come from lower in the atmosphere. In particular, they are expected to come from various combinations of waves—gravity waves, tides, and planetary waves—that have their origins at lower altitudes and grow exponentially as they propagate upward. Hence, to understand this region and to understand the forcing functions that affect it, observations of this region have to be complemented with observations extending throughout the mesosphere and into the stratosphere. This can be done with the appropriate mix of lidar observations. This DURIP upgrade has provided considerable hardware that will enable the two ALO lidars to provide many appropriate observations from 30 km to 105–110 km, with an emphasis on greatly improving the observations between 80 and 105–110 km.

To understand this introduction and see where the research is going, it is necessary to have some background information on the structure and properties of the mesosphere leading up to the edge of space. When mean zonal wind and temperature patterns throughout the region were constructed [e.g., *Murgatroyd*, 1957], they showed a stratosphere that was basically in radiative equilibrium (except for the polar winter) and a mesosphere that was not in radiative equilibrium. This manifested itself in two ways: the summer mesopause temperature was much colder than the winter mesopause temperature, and the mesospheric jets (winds toward the east in winter and toward the west in summer) were much slower than expected. Calculations and modeling showed that substantial agreement could be obtained by introducing a Rayleigh friction term to decelerate the mesospheric jets [*Leovy*, 1964; *Schoeberl and Strobel*, 1978; *Holton and Wehrbein*, 1980; *Geller*, 1983; *Garcia and Solomon*, 1983]. This produced a meridional circulation from summer to winter that induces vertical motions leading to adiabatic cooling in the summer hemisphere and compressional heating in the winter hemisphere. Meanwhile, the dissipation of vertically propagating gravity waves was proposed as the source of this drag [*Hines*, 1960; *Lindzen*, 1967]. These gravity waves are believed to originate in the troposphere, the most often suggested sources being orography [e.g., *Nastrom and Fritts*, 1992; *Bacmeister*, 1993], convective storms [e.g., *Alexander et al.*, 1995; *Alexander*, 1996], and the jet stream [e.g., *Fritts and Nastrom*, 1992; *Tsuda et al.*, 1994]. However, what is important for what is happening at the edge of space is the existence of these waves, not their source. As they propagate upwards, conservation of energy arguments say that the wave amplitude will grow by a factor of *e* every two-scale heights (approximately every 14 km) until energy dissipation (saturation or "breaking") sets in. This growth would be more than two orders of magnitude between the troposphere and the upper mesosphere. It became practical to test the effects of breaking gravity waves, (i.e., eddy forcing) in model calculations after a scheme was proposed for the parameterization of momentum deposition (wave drag) and turbulent (eddy) diffusion [*Lindzen*, 1981]. Several investigators tested the effects of wave drag [e.g., *Holton*, 1982, 1983]; others tested the combined effects of wave drag and turbulent diffusion [e.g., *Garcia* and *Solomon*, 1985; *Le Texier et al.*, 1987]. The success of these and similar calculations in accounting for the major dynamical features of the mesosphere and for the distribution of minor constituents in the mesosphere (and hence variations in emissions such as OH), have lent strong support to the central role of gravity waves in accounting for the middle atmosphere circulation and the departures from radiative equilibrium.

Because these waves grow greatly in amplitude with increasing altitude, a wave that is barely detectable at 30 km, becomes easily detectable—to the appropriate instrument—at the edge of space. Rayleigh-scatter lidars [*Hauchecorne and Chanin*, 1980; *Chanin and Hauchecorne*, 1981; *Wickwar et al.*, 2000] have been used extensively to observe the effects of these waves up to approximately 80–85 km and resonance-scatter lidars to probe the 80–105 km region. Originally, resonance scatter was used by the Illinois group to determine gravity wave parameters from density fluctuations. More recently, resonance scatter from sodium and potassium have been used to examine neutral temperatures and their fluctuations in this region [e.g., *Neuber et al*, 1988; *She et al.*, 1993; *Senft et al.*, 1994; *von Zahn and Höffner*, 1996; *von Zahn et al.*, 1996; *She and von Zahn*, 1998; *States and Gardner*, 2000a,b; *She et al.*, 2000]. The resonance capability has also been extended to winds [e.g., *Bills et al.*, 1991; *Gardner and Yang*, 1998] and fluxes [*Gardner and Yang*, 1998]. Fluxes of momentum, heat, and constituents can be derived with sensitive enough lidars.

With the components purchased for ALO under this DURIP grant, Rayleigh observations will shortly be extended to 100 km to provide temperatures and densities; and (simultaneous) resonance observations will be added to provide temperatures and winds. Both lidars will also be able to examine structures. The combined effect will be to provide continuous and simultaneous data from 30 km through 105–110 km. Currently, students are assembling and testing the components for this greatly upgraded system.

Much of the research today in the mesosphere and edge of space is directed at understanding what waves propagate upward under what conditions and how they interact with the background atmosphere and with each other. For instance, at this time large temperature variations are seen with Rayleigh lidar in winter in the mesosphere at mid latitudes. These mesospheric inversion layers [*Hauchecorne et al.*, 1987; *Whiteway et al.*, 1995] can produce temperature oscillations about the mean of 25 to 40 K. This phenomenon is believed to be related to tides [e.g., *Meriwether et al.* 1998], but tidal theory cannot currently predict anything of this magnitude. A possible explanation lies in the enhancement of the tidal oscillations by interaction with gravity waves, but this remains to be seen. An unknown aspect of these oscillations is what they are like at the edge of space. If this phenomenon has a vertical wavelength associated with it, as is suspected, then there should be a significant disturbace at the edge of space. This could be readily determined with the new ALO capability of simultaneous resonance-scatter lidar observations. Accompanying these temperature oscillations, there would be large density oscillations and probably large fluctuations in IR emissions.

Another example of effects in this altitude region that are being studied is sharp step-function like changes in airglow emission intensity and temperature [*Taylor et al.*, 1995]. It appeared as a straight edge moving across the sky at the edge of space. *Dewan and Picard* [1998] have explained this in terms of a bore, such as moves up a coastal river when the tide comes in. This explanation comes with a clear prediction that the bore should be closely associated with a mesospheric inversion layer. This could be examined by a combination of lidar and all-sky camera (ASC) observations. Rayleigh lidar observations are needed to detect the inversion layer and density perturbations. Resonance lidar observations are needed to examine the temperatures and winds in the altitude region where the step function is seen and a multi-wavelength ASC is needed to relate the new observations to the previous ones.

Another phenomenon to be examined is the occurrence of noctilucent clouds at 82–83 km at mid latitudes, at 41.7°N. They were detected totally unexpectedly at ALO near summer solstice in 1995 and 1999. One implication of these detections is a significant cooling of the edge of space region. Such cooling has been linked to global warming at lower altitudes. While the old system could detect these clouds [*Wickwar et al.*, 2002], it will take the upgraded lidar systems to determine the conditions under which they occur.

At the higher altitudes, some of the research effort that will be possible with this upgrade will be to examine what effects arise from space weather, i.e., from solar cycle variations and geomagnetic activity. At mid latitudes, much of this still has to be determined.

This discussion has concentrated so far on an altitude region, the edge of space. It needs to be extended to latitudinal differences. The upgraded ALO complements the Na lidar that AFOSR is supporting at ALOMAR at 69°N and the scientific observations it is supporting at AEGIS at 21°N through the Maui-MALT program. Thus AFOSR is making significant contributions to lidar observations of the edge of space at both high and low latitudes. It is expected that significantly different results will be forthcoming from the mid-latitude observations at ALO at 42°N. Strong latitudinal variations, even unique differences, do exist. They need to be observed to properly specify the edge of space at mid latitudes and to move towards physics-based predictions in the future.

One of the important aspects of the mid-latitude mesosphere is the mesospheric jet, which flows to the east in winter and to west in summer. It modulates which waves (gravity waves, tides, and planetary waves) can propagate upwards. It is centered at mid latitudes [*Fleming et al.*, 1996; *Labitzke and van Loon*, 1999]. Accordingly, it will significantly affect the waves that can propagate to the edge of space at mid latitudes and will affect the temperature structure. Mesospheric temperature profiles seen at 69°N [*Lübkin and von Zahn,* 1991] differ significantly from those seen at ALO at 42° N [*Wickwar et al.*, 2000] throughout the year. The high-altitude, high-latitude temperatures are colder in summer, as expected, but are remarkably similar in winter. A significant decrease occurs in the temperature gradient at higher altitudes at mid latitude that does not appear in the high-latitude results. These differences further imply differences in the meridional winds and vertical drifts that dominate the physics controlling the temperature structure near the edge of space.

Another, apparently mid-latitude phenomenon is that of mesospheric inversion layers [e.g., *Hauchecorne et al.*, 1987; *Whiteway et al.*, 1995, *Meriwether et al.* 1998], which have already been discussed. In winter, these are extremely strong fluctuations of temperature and density with altitude. They would lead to strong changes in integrated emission, in the densities that would be encountered by bodies leaving or entering the edge of space, and in the boundary conditions for the thermosphere. Space-based observations indicate that they are confined to mid latitudes. This is partially confirmed by the paucity of inversion-layer observations at Sondrestrom at 67° N [Private communication, Jeff Thayer] and Fairbanks at 65° N [*Cutler et al.*, 2001].

In addition, tidal modes differ with latitude, [e.g., *Manson et al.*, 1999]. This presumably reflects a combination of forcing and transmission. In a similar vane, planetary waves often extend into the mid-latitude region in winter [*Hauchecorne and Chanin*, 1982; *Nelson*, 2003], where they give rise to considerable variability in mesospheric temperature that propagates upwards to the edge of space. They do not appear to reach low latitudes.

In addition to these phenomena, there may be aspects of global change that are appearing at mid latitudes. Without mid-latitude observations, we would be unaware of these changes. In particular, near equinox in June 1995 and June 1999, we saw noctilucent clouds with the lidar above Logan, UT. This might be the result of temperature changes brought on by changes in CO_2 and CH_4 concentrations in the atmosphere [*Thomas*, 1996], or they might be the result of global change leading to increased meridional circulation [*Wickwar et al.*, 2002]. In either case, their presence would significantly affect the background IR radiation in the atmospheric windows at 10–13 and 17–25 μm.

Another mid-latitude difference is that of auroral precipitation. Sensitive optical instruments often detect auroras at mid latitudes [*Rassoul et al.*, 1993]. Some are auroral red arcs [*Rees and Roble*, 1975] that occur high in the thermosphere. But many others have green rays and other emissions that are indicative of their originating near the mesopause. The excitation mechanisms are not simply the same as at high latitude. They are thought to be from ring-current ions lost from the ring current by charge exchange with neutrals. It remains to be seen if there are sufficient such energetic neutrals to heat the upper altitudes accessible with lidar.

Thus, several phenomena are centered at mid latitudes and several extend into it from higher or lower latitudes. Their presence gives rise to a clear need for mid-latitude observations. It is not possible to infer what is happening in this latitude region by interpolating observations from higher and lower latitudes.

3. THE ALO UPGRADE

This grant for $198,352 was for equipment to be added to and incorporated into the existing lidar system to enable good observations to be made at the edge of space using both the Rayleigh and resonance lidars. From a budget point of view, the expenses were divided into six categories in the original proposal. These categories are being followed in this report. The first category involved the components to upgrade the large telescope cage to enable it to point towards different parts of the sky under computer control from the control room, one floor below, and to transfer the optical signals from the four coaligned telescopes to the detector chamber, also one floor below. More specifically, this involved purchasing motors, gear boxes, and encoders to control the elevation and azimuth motion; limit switches to limit the azimuth motion to ±270° from the home position towards the north, and the elevation position up to 45° off the zenith. It involved access between floors, running cables for 240 VAC power, engineering supports for the gearboxes and motors, purchasing a hoist to lift the equipment into place, machining, and welding. It also involved a computer for pointing control and interfacing between the computer and the motors, and the optical fibers to transfer the signals to the detector chamber. Some of the power, control cables, and optical fibers needed mounts and flexible conduit that would allow them to properly flex without being harmed when the telescope changed direction. The vendors, items purchased, and prices are listed in Table 1.

Table 1. Telescope Pointing in Azimuth and Elevation and Control

Vendor	Description	Amount
Kaman Industrial Technology	Azimuth and Elevation drive systems for telescope	$17,898.00
Bsumek Mu and Assoc, PC	Structural evaluation for azimuth & elevation system	$1,925.00
Steven Reed	Make and install trap doors in observatory floor	$440.00
Physical Plant - USU	Drop cords for lasers, move hatch, move light switch (1 of 4)	$2,931.32
Physical Plant - USU	Drop cords for lasers, move light switch (2 of 4)	$70.56
Physical Plant - USU	Design fee for work in laser room, control room, and obs. (3 of 4)	$355.00
Physical Plant - USU	Move hatch and light switch (4 of 4)	($13.56)
Anderson Lumber	Wire, bolts, clips, cable for laser room	$43.11
Thomson Electric Supply	Cord, electrical components for lighting in laser room	$120.54
Lowe's Home Improvement	Plywood, light globes, cement	$63.14
Lowe's Home Improvement	30-ft braided tubing	$9.60
Deanox	Computer system	$850.30
Computerwise	Serial port card for PC	$49.00
National Instruments	Modules, terminal base, power supply for az & el system control	$1,984.50
Lowe's Home Improvement	Batteries, glue, connectors	$18.62
Lowe's Home Improvement	PVC pipe	$53.36
Anderson Lumber	Light switch	$4.89
Radio Shack	Misc. electrical supplies	$38.62
Lowe's Home Improvement	Misc. building supplies	$191.44
Lowe's Home Improvement	Pulley and rope to move az & el gear reducers and motors	$18.33
Ipaco	Machine a key slot in elevation axle	$100.00
Radio Shack	Electrical wire	$4.49
T. Wynn (Walmart/McMaster)	Snaps and metal stock	$13.21

Table 1. Telescope Pointing in Azimuth and Elevation and Control		
Vendor	**Description**	**Amount**
Lowe's Home Improvement	PVC pipe, broom, dust pan for cable stand offs around az axis	$41.40
Lowe's Home Improvement	Conduit and brackets for control wiring	$29.62
Sears Roebuck	Tool box for parts and tools	$457.89
Lowe's Home Improvement	Nuts, bolts, washers	$35.14
Troy Wynn (Home Depot)	Misc. building supplies	$30.42
Radio Shack	Misc. electrical supplies	$29.08
Lowe's Home Improvement	Cables and connectors	$48.45
Ipaco	Metal tubing and plates for az & el system installation	$92.89
Ipaco	Steel tubing for azimuth & elevation system installation	$10.47
Physical Plant - USU	Electrical work for azimuth & elevation motors	$1,690.85
Industrial Tool and Supply	Chain hoist for elevation drive installation	$72.71
Toone Stainless	Welding--installation of az & el gear reducers & motors	$800.00
CVI-West	6-axis custom lens-to-fiber assembly for telescope	$3,800.00
Thorlabs Inc.	Four optical fibers & protective sheaths: 1.5-mm dia. & 0.39 NA	$6,107.40
	Total	$40,415.79

The second category involved the directional control of the two laser beams from their leaving the lasers, passing through the telescope cage, and going into the sky aligned with the telescope. More specifically, it involved their detection and control on the optical table, their going vertically from the laser room to the observatory along the telescope azimuth axis, following a path through the telescope cage, and being controlled to emerge pointing parallel to the four telescopes. On the optical table, this involved optical pickoffs, CCD cameras, closed-loop servo systems (motors, power supplies, controllers, encoders), a computer to analyze the images and direct the servo systems, choppers, detectors, and an air cleaner to minimize dust on the laser table. It also involved a detector channel and a chiller to help reduce the background signal. The vendors, items purchased, and prices are listed in Table 2.

Table 2. Directional Control of Laser Beams		
Vendor	**Description**	**Amount**
Atmospheric Research Systems	Set up lasers, lidar receiver, alignment, zero-Doppler system	$10,214.00
Thermo Oriel	Chopper system and chopper wheel	$1,244.00
Products for Research	PMT housing: liquid heat exchanger and shutter assembly	$3,284.00
Electron Tubes, Inc	9954A Photomultiplier Tube (PMT)	$681.00
Intermountain Optics	Grind and polish six 8-inch mirrors and 1 beamsplitter	$3,000.00
Affinity Industrial Inc.	Recirculating chiller to help cool PMTs	$2,195.00
Intermountain Optics	Seven single-surface mirror substrates (BK7 & Quartz)	$7,915.00
Thermo Oriel	Repair chopper	$175.00
Bennett's Paint	Paint and brushes for laser room	$13.33
Staples	Wireless phones for observatory and control room	$59.88
New Focus	Chopper and controller for detection system	$2,115.00
MilesTek Corporation	Cables	$180.00
CVI Laser Corp	Optical & mechanical components for laser table and telescope	$12,429.00
Deanox	Computer system	$867.26
National Instruments	Motion controllers and bus cables for beam steering	$3,038.00
National Aperature	Multi-function servo-amplifier sys. and cable for beam steering	$5,353.25
National Instruments	PCI-GPIB and cable to interface choppers to computer system	$632.50
USU Bookstore	4-port computer hub	$49.99
Radio Shack	Headphones for computer	$29.99

Table 2. Directional Control of Laser Beams		
Vendor	**Description**	**Amount**
ThorLabs	Beam dump for pulsed laser	$285.00
Thorlabs Inc.	Rails, nuts, cubes, screws for detector housing	$424.00
Thorlabs Inc.	Filters, lens tube, and ring	$230.00
SignPro	Sheet of foam PVC for detector housing	$136.50
Thorlabs Inc.	Lens and mount	$124.20
Thorlabs Inc.	Long structural rail for detector housing	$98.00
Thorlabs Inc.	Motorized actuators for beam steering	$4,492.50
Watec America Corporation	Two cameras and power supplies for laser-beam pointing	$607.50
New Focus	Chopper and controller	$2,010.00
Thorlabs Inc.	ND filters, adapter, lens mount, retaining ring, spanner wrench	$1,788.89
CVI	Beam expanders, lens, dichroics, mirrors, choppers	$6,842.70
LowestDollar.com	Austin HealthMate--HEPA-filter air cleaner for optical room	$400.00
	Total	$70,915.49

The third category involved the final alignment of the laser beams, as they leave the telescope cage, and the telescopes. The components include two additional CCD cameras near the top of the telescope cage and a computer to analyze the images and give commands to the servo motors controlling two mirrors in the telescope cage. They also include four narrow bandwidth interference filters to be placed in front of the four detectors to spectrally separate the lidar return from the background signal. These filters will enable the alignment of the four telescope mirrors to be adjusted to maximize the received signals. The vendors, items purchased, and prices are listed in Table 3.

Table 3. Laser Beam Alignment		
Vendor	**Description**	**Amount**
OptoSigma Corporation	Optical baseplate and angle bracket	$560.00
Barr Associates, Inc	Interference filters at 770 and 532 nm	$6,324.00
Insight	CCD cameras for beam steering	$795.00
Deanox	Computer	$890.12
Staples	Computer monitor	$159.98
	Total	$8,729.10

The fourth category involved the alexandrite laser, which excites the resonance backscatter from potassium. The purchases are to control the wavelength of the laser and to characterize the output of the laser. More specifically, the alexandrite underwent a significant upgrade that included refurbishing the pump chambers to make them more efficient and changes to the optics and power supplies to enable the laser to operate at 30 Hz, the same rate as the Nd:YAG laser. This enables the two lasers to operate simultaneously, which is required to obtain complete profiles. To obtain temperatures and winds from the potassium returns, the wavelength of the alexandrite has to be carefully controlled. The purchases included a "head" for the seed laser to do the actual wavelength control and upgrades to the capacitance stabilized Fabry-Perot etalon (CSE) that will control the seeder and to the laser wavemeter (LWM) that will be used to check the wavelength, spectral width, and power of each laser pulse. Optical components were purchased to pickoff a very small portion of the alexandrite beam and direct it into the LWM. A computer was purchased to control all these components and a counter-timer card to help control the system timing. The data-acquisition system, including the data-acquisition software, had to be modified to also include the alexandrite laser and the backscattered signal from potassium. Miscellaneous items included such things as a file cabinet to hold manuals, filter calibration curves, etc. The vendors, items purchased, and prices are listed in Table 4.

Table 4. Wavelength Control and Characterization of Alexandrite Output		
Vendor	**Description**	**Amount**
Light Age, Inc.	Alex. laser--pump chambers refurbished, power supplies, 30 Hz	$28,300.00
Hovemere, Ltd	Modification of CSE and LWM computer interfacing	$20,686.00
Newport EOSI	Laser diode module--seeder for alexandrite laser	$3,250.00
Buy.Com	8-port dual speed computer switch for data-acquisition network	$85.91
Physical Plant - USU	Drop cords for lasers, move hatch, move light switch	$2,494.17
Hovemere, Ltd	Power supply, equipment rack, PMT, data acquisition program	$7,500.00
Baileys Moving & Stor.	Transport of equipment rack & equipment (1 of 2)	$1,941.67
Baileys Moving & Stor.	Transport of equipment rack & equipment (2 of 2)	$770.00
Vince Wickwar	Reimbursement for motherboard and CPU for data acq. computer	$215.98
Deanox	Computer monitor	$185.00
National Instruments	Counter/timer board, shielded cable, BNC conn. box--sys. timing	$1,015.50
Staples	APC UPS systems for computers in observatory network	$624.75
Staples	Network hub	$49.98
Surplus Sales	Printer, scanner, file cabinets for lidar control room	$355.00
Optosigma	OPT carriers for beam expanders	$284.25
CVI Laser Corp	Beam expander lenses and other lenses	$780.00
Lowe's	Multimeter	$84.22
	Total	$68,622.43

The fifth category included the purchase of an aircraft avoidance radar. With the laser beam pointing off zenith it becomes essential to have such a radar. This category included the purchase of the same solid-state, marine radar that had been implemented and approved at the lidar at the Millstone Hill Incoherent-scatter radar facility. It included the power supply, a horn antenna to be mounted coaxial to the laser beam in place of the original horizon scanning antenna, a computer to interface between the radar and the data-acquisition system, and reimbursement for flight time of a small aircraft used to test the low-altitude capability of the radar. The vendors, items purchased, and prices are listed in Table 5.

Table 5. Aircraft Avoidance Radar		
Vendor	**Description**	**Amount**
Furuno USA, Inc.	Radar system for aircraft detection	$4,671.25
Standard Supply	Power supply for radar system	$255.00
L-3 Comm. Corp	X-Band horn antenna to modify radar system	$468.00
Deanox	Computer system	$915.01
National Instruments	Controller, interface, cable for computer I/O	$1,746.00
Jamon Neilson	Reimbursement for flight time to test radar system	$49.50
	Total	$8,104.76

The sixth category included most of the large shipping and custom charges. The vendors, services, and prices are listed in Table 6.

Table 6. Other Direct Expenses		
Vendor	**Description**	**Amount**
Federal Express	Return old power supply to Light Age, Inc.	$182.24
Federal Express	Return 2nd old power supply to Light Age, Inc.	$141.69
Federal Express	Ship CSE & LWM controllers to Hovemere, Ltd	$126.38
Cargo Link International	Freight & duty	$207.06
Consolidated Freightways	Freight for chiller from Affinity, Inc.	$152.78
Consolidated Freightways	Ship frequency-control parts for Az & El systems from Rockwell	$65.40
DHL Airways	Customs processing charges	$30.00
Federal Express	Shipment to Hovemere, Ltd. for modifications	$658.88
	Total	$1,564.43

4. COMPARISON TO OTHER LIDAR SYSTEMS

In this section the two ALO lidars are compared to several other lidars to indicate what this upgrade will have accomplished when all the new components are installed and operating. In particular, ALO needs to be compared to ALOMAR and AEGIS, both of which AFOSR has helped to implement and is helping to operate. To be meaningful, these comparisons include several different characteristics. The most important one is high sensitivity for resonance scatter observations. These provide temperature and wind observations at the edge of space. Second, wind observations and direct observations of structure depend on the ability of the telescope to move in azimuth and elevations. Third, to understand the origin of what is observed in this region, it is important to know what propagates up from below. This requires great sensitivity for Rayleigh scatter observations. Fourth, learning about this region, like any region of space, requires many nights of observation: first to elucidate the normal behavior, then to determine the unusual behavior.

Several lidar systems are compared in Table 7. These include ALO, ALOMAR, and AEGIS as well as the alexandrite lidar at IAP (Kuhlungsborn, Germany), the Na and Rayleigh lidars at PCL (University of Western Ontario), and the Na lidar at CSU (Ft. Collins, CO). The IAP lidar is included because it was the first potassium lidar in operation. The PCL is included because it is the other large lidar in the world. The CSU lidar is included because it has figured in so much of the research based on Na observations. To compare sensitivities, we compare a modified version of the parameter called the "figure of merit". It was developed in recent years to compare Rayleigh-scatter lidars. It is the product of the laser power and the unobstructed area of the receiving telescope: it is given in units of W-m^2. In its original version, the figure of merit was applied to Rayleigh-scatter lidars operating at one wavelength, 532 nm. It can be extended to resonance scatter. In this case, a change in wavelength means a change in scattering constituent, i.e., from sodium at ALOMAR, AEGIS, and CSU to potassium at ALO and IAP. To be meaningful, the relative densities of the two constituents and the relative scattering cross sections have to be taken into account. In addition, when the emitted beam or the backscattered signal is split, that needs to be taken into account. These factors are included in the figures of merit in the resonance-scatter portion of Table 7. Because the Rayleigh scatter cross section is proportional to λ^{-4}, where λ is wavelength, the wavelength has to be taken into account. Again, when the emitted beam or the backscattered signal is split, that needs to be taken into account. They are included in the figures of merit in the Rayleigh-scatter portion of Table 7. The details of the corrections are given in the footnotes to the Table.

The comparison of the alexandrite-based resonance lidar at ALO to the one at IAP shows a figure of merit that is 16 times bigger at ALO than at IAP. This factor is mostly because of the different telescope sizes. Everything else being equal, it implies that similar results could be obtained in 1/16th the time at ALO as at IAP. Similarly, ALO observing potassium will be much more sensitive than CSU observing sodium. However, the situation changes when ALO observing potassium is compared to ALOMAR and AEGIS observing sodium. This comes about mainly because sodium is more abundant by a factor that varies between 40 and 140 depending on season [*Eska et al.*, 1999; *Plane et al.*, 1999]. The large figures of merit for ALOMAR and AEGIS enable them to measure several types of fluxes in addition to temperatures and winds, e.g., *Gardner and Yang* [1998]. Nevertheless, the value for ALO is large enough that it will be able to do a very good job measuring temperatures and winds, and should be able to determine heat fluxes as done by *Tao and Gardner* [1995] using a Na system with a figure of merit of 0.50 W-m^2.

However, thinking of the future, it should be noted that an alexandrite laser can be used to observe sodium. This is more complicated than observing potassium: the laser output has to be changed to 792 nm, Raman shifted in H_2, and frequency doubled to obtain 589 nm. Taking into

Table 7. Lidar comparisons for Resonance and Rayleigh Scatter

Lidar	ALO	IAP[1]	ALOMAR[2]	AEGIS[3]	PCL[4]	Ft.Collins[5]
Resonance Scatter from Potassium (K) or Sodium (Na)						
Emission & λ (nm)	K at 770	K at 770	Na at 589	Na at 589	Na at 589	Na at 589
Energy (mJ)	150	100	30	30	60	30
Pulses / sec (Hz)	30	25	30	40	20	50
Power (W)	4.5	2.5	0.90	1.2	1.2	1.5
Aperture Dia (m)	2.5	0.80	1.8	3.6	2.6	0.36
Correction Factor[6]	0.011	0.011	0.50[7]	0.50[8]	1.0	0.50[7]
Figure of Merit (W-m^2)	0.23[9]	0.014[9]	1.1	5	6.6	0.074
Rayleigh Scatter						
Emission λ (nm)	532 nm	770 nm	532 nm	589 nm	532 nm	589 nm
Power (W)	18	2.5	12	1.2	12	1.5
Correction Factor[10]	1.0	0.23	0.50[11]	0.66	1.0	0.66
Figure of Merit (W-m^2)	84	0.29	14	6.9	66	0.10
Pointing						
Pointing Capability	Yes	Zenith	Yes	Yes	Zenith	Limited

[1]*von Zahn and Höffner* [1996] and *Eska et al.* [1999].
[2]Estimated assuming 30 Hz to interleave with Nd:YAG and 30 mJ per pulse as a commonly achieved value.
[3]Assumed the same as SOR. Worked backwards from *Gardner and Yang* [1998] figure of merit of 10.
[4]*Sica et al.* [1995] and *Argall et al.* [2000].
[5]Based on memory of upgraded system seen in June 2000.
[6]Based on the ratios of peak number densities and scattering cross sections, i.e.,
$[N_{MAX}(K) / N_{MAX}(Na)] \times [\sigma(K) / \sigma(Na)] = [5.0\times10^7 / 4.0\times10^9] \times [1.34\times10^{-15} / 1.52\times10^{-15}] = 1.10\times10^{-2}$
[*Eska et al.*, 1999; *Plane et al.*, 1999; *Megie*, 1988; *Gardner*, 1989]
[7]Reduced because the output is split between two telescopes.
[8]Reduced by 0.5 because returned signal had to be reduced by between 0.25 and 0.50 [*Gardner and Yang*, 1998].
[9]The alexandrite laser could also excite Na at 589 nm by operating at 792 nm, Raman shifting to 1178 nm, and frequency doubling. The design specification for the ALO laser was 15 mJ per pulse at 589 nm, which would give a resonance figure of merit of 2.1 W-m^2. Similarly, it would give approximately 0.13 W-m^2 for the IAP laser.
[10]Based on normalizing the Rayleigh scatter to 532 nm, i.e., $(532 / \lambda)^4$.
[11]Reduced because half the light goes to the normal Rayleigh-Mie channel and half goes to the Doppler Wind and Temperature System (DWTS).

account a smaller output at 792 nm than at 770 nm and inefficiencies in Raman shifting, the figure of merit for sodium should be 2.1 W-m^2, i.e., in the range of ALOMAR and AEGIS. That this could be done is strongly supported by laboratory work at ALO on water vapor absorption using Raman-shifted alexandrite output [*Hammond et al.*, 2002]. At some point, this change to sodium may be worth considering.

The next important consideration is the relative sensitivity for Rayleigh-scatter observations. As seen in Table 7, the upgraded ALO is the most sensitive: it has the highest figure of merit. It is much greater than for AEGIS, because ALO uses a different laser for Rayleigh scatter than for resonance scatter. This may change at AEGIS, but the optical system would also have to be greatly modified. The ALO sensitivity is also much greater than for IAP and CSU for the same reason and because the collecting area is so much greater. These two lidars were never intended for significant Rayleigh-scatter observations. ALO is more sensitive than PCL because it uses a more powerful Nd:YAG laser. Thus, the upgraded ALO is the most sensitive of the Rayleigh-scatter lidars.

In addition to relative sensitivities, another important characteristic for these lidars is the ability to point off zenith. This is essential for wind and structure measurements. This upgrade gave ALO the ability to point to any azimuth and to any zenith angle down to 45° off zenith. Thus it joins ALOMAR and AEGIS in having an off-zenith pointing capability. Of the other lidars in Table 7, PCL cannot because its mirror is a spinning "bowl" of mercury, the IAP telescope is fixed in zenith, and the CSU lidar uses two fixed telescopes to measure winds.

Another important consideration, one which is not mentioned in Table 7, is the number of nights a year that the lidar can observe. With ALO on the USU campus and dedicated to atmospheric observations, it is feasible to observe many more hours than at most other facilities. ALO can easily observe 100 nights a year and has observed as many as 140 nights. The main limitations have been funding and down time for repairs, not weather. In contrast, AEGIS is limited to 25 nights a year because of other demands for the telescope. And, ALOMAR is in a region that is considerably cloudier than ALO.

In summary, the components have been purchased to make major upgrades to the two lidars at ALO. Some have already been incorporated into the system (with other funding), and others are being incorporated. A comparison of specifications for the upgraded ALO with other lidars shows that ALO will obtain very good temperatures and structure results at the edge of space. It should also be the first resonance lidar observing potassium to obtain Doppler wind measurements. (However, it would not be able to do as well as ALOMAR and AEGIS in determining fluxes, but if observations are switched from potassium to sodium in the future, it should be able to perform at a level between ALOMAR and AEGIS.) In addition, because of its extreme Rayleigh sensitivity, it will be able to obtain excellent information on the many effects that propagate up from below into the near-space region. Furthermore, assuming sufficient ongoing funding, ALO will continue to observe more nights a year than most other lidars.

5. IMPACT ON EDUCATION

Unlike the lidars that AFOSR supports at ALOMAR and AEGIS, this facility is located right on the campus of a research university. As, literally, the most visible science experiment on the USU campus, ALO has attracted considerable student interest. Between 5 and 7 undergraduates work on the lidar project at a given time. They are involved in acquiring the data, reducing the data, helping to show interested groups the research and the facility, and developing the website. Some of them, as well as additional physics majors, become involved in the research doing their senior projects on the lidar. They present their results on campus at the Student Showcase in April or nationally at the CEDAR Workshop in late June. Approximately three of the students participate in the CEDAR Workshops each year. One of the students this year has applied to present her research results at a special "Posters on the Hill" session to be held in the rotunda of the U.S. Capitol this coming spring. Some of these undergraduates have stayed here to work on the lidar as graduate students. Others have gone on to do graduate or profession work elsewhere. From their participation, they gain a variety of unique educational experiences.

So far, two students, one an AF officer attending USU under the auspices of AFIT, have obtained their PhDs based on lidar work. Two MS and one PhD student are currently working on the project (supported by other funds). One of the MS students and the PhD student have been heavily involved with this DURIP upgrade. They have participated extensively in determining the characteristics of the lasers, selecting the components purchased, testing them, integrating them into the system, and programming portions of the data-acquisition system. One of these students also talked a well-known local company in the area of laser diagnostics, Spiricon, into providing USU with the equipment needed to measure the beam divergence of the two lasers. This information, surprisingly, was unavailable from the manufacturers, but was vital for properly choosing some of the optical components for the upgrade.

Because the alexandrite laser was about to go on line, two undergraduates this past year worked on physics-based models of the Doppler-free potassium signal and the backscattered potassium signal from the alexandrite laser. These were done as senior projects. Both of the models were needed to make the best use of the alexandrite laser. Another undergraduate student is working with the Doppler-free hardware this spring to help bring the alexandrite laser on line. The PhD student will include the first simultaneous Rayleigh and potassium temperature data from the upgraded system in his dissertation.

In addition to research and university education, the lidar—situated in a valley with a 100,000 population—has attracted considerable interest from the public at large. Newspaper articles on campus, in Logan, and in Salt Lake City as well as a radio interview have added to that attention. Discussions and tours have been given for grade-school children, Career Night, Expanding Your Horizons, boy scouts, high-school students, home-schooled students, prospective college students, and many individuals and small groups. In all, since August 1993, the facility has been shown to more than 1000 visitors.

This project should shortly have further impact on education. When the beam starts to move in the sky, it will have a big impact on campus and in the valley. It will attract the attention of even more students, which should give us a bigger pool from which to select high caliber students. More groups will want to visit the facility to find out about the project. Then, as papers start to appear from this unique, upgraded facility, it will become easier to recruit graduate students and post docs from around the country.

6. REFERENCES

Alexander, M.J., A simulated spectrum of convectively generated gravity waves: Propagation from the tropopause to the mesopause and effects on the middle atmosphere, *J. Geophys. Res.*, *101*, 1571–1588, 1996.

Alexander, M.J., J.R. Holton, and D.R. Durran, The gravity wave response above deep convection in a squall line simulation, *J. Atmos. Sci.*, *51*, 2212–2226, 1995.

Argall, P.S., O.N. Vassiliev, R.J. Sica, and M.M. Mwangi, Lidar measurements taken with a large-aperture liquid mirror. 2. Sodium resonance-fluorescence system, *Appl. Opt.*, *39* (15), 2393–2400, 2000.

Bacmeister, J.T., Mountain-Wave Drag in the Stratosphere and Mesosphere Inferred from Observed Winds and a Simple Mountain-Wave Parameterization Scheme, *J. Atmos. Sci.*, *46*, 377–399, 1993.

Bills, R.E., C.S. Gardner, and C.-Y. She, Narrowband lidar technique for sodium temperature and Doppler wind observations of the upper atmosphere, *Opt. Eng.*, *30*, 13–21, 1991.

Chanin, M.-L., and A. Hauchecorne, Lidar observation of gravity and tidal waves in the stratosphere and mesosphere, *J. Geophys. Res.*, *86*, 9715–9721, 1981.

Cutler, L.J., R.L. Collins, K. Mizutani, and T. Itabe, Rayleigh Lidar Observations of Mesospheric Inversion Layers at Poker Flat, Alaska (65°N, 147°W), *Geophys Res. Lett.*, *28* (8), 1467–1470, 2001.

Dewan, E.M., and R.H. Picard, Mesospheric bores, *J. Geophys. Res.*, *103*, 6295–6305, 1998.

Eska, V., U. von Zahn, and J.M. Plane, The terrestrial potassium layer (75–110 km) between 71 S and 54 N: Observations and modeling, J. Geophys. Res., 104, 17173–17186, 1999.

Fleming, E.L., S. Chandra, M.D. Burrage, W.R. Skinner, P.B. Hays, B.H. Solheim, and G.G. Shepherd, Climatological mean wind observations from the UARS high-resolution Doppler imager and wind imaging interferometer: Comparison with current reference models, *J. Geophys. Res.*, *101*, 10455–10473, 1996.

Fritts, D.C., and G.D. Nastrom, Sources of mesoscale variability of gravity waves. Part II: Frontal, convective, and jet stream excitation, *J. Atmos. Sci.*, *49*, 111–127, 1992.

Garcia, R.R., and S. Solomon, A numerical model of the zonally averaged dynamical and chemical structure of the middle atmosphere, *J. Geophys. Res.*, *88*, 1379–1400, 1983.

Garcia, R.R., and S. Solomon, The effect of breaking gravity waves on the dynamics and chemical composition of the mesosphere and lower thermosphere, *J. Geophys. Res.*, *90*, 3850–3868, 1985.

Gardner, C.S., Sodium resonance fluorescence lidar applications in atmospheric science and astronomy, *Proc. IEEE*, *77* (3), 408-418, 1989.

Gardner, C.S., and W. Yang, Measurements of the dynamical cooling rate associated with the vertical transport of heat by dissipating gravity waves in the mesopause region at the Starfire Optical Range, New Mexico, *J. Geophys. Res.*, *103*, 16909–16926, 1998.

Geller, M.A., Dynamics of the middle atmosphere, *Space Sci. Rev.*, *34*, 359–375, 1983.

Hammond, M.R., T.D. Wilkerson, and V.B. Wickwar, High-resolution spectra of atmospheric water vapor in the near-IR using a Raman-shifted alexandrite laser, in *Lidar Remote Sensing for Industry and Environment Monitoring II*, edited by U.N. Singh, Proceedings of SPIE Vol. 4484, 103–111, 2002.

Hauchecorne, A., and M.L. Chanin, Density and temperature profiles obtained by lidar between 35 and 70 km, *Geophys. Res. Lett.*, *7*, 565–568, 1980.

Hauchecorne, A., and M.L. Chanin, A mid-latitude ground-based lidar study of stratospheric warmings and planetary wave propagation, *J. Atmos. Terr. Phys.*, *44*, 577-583, 1982.

Hauchecorne, A., M.L. Chanin, and R. Wilson, Mesospheric temperature inversion and gravity wave breaking, *Geophys. Res. Lett.*, *14*, 933-936, 1987.

Hines, C.O., Internal atmospheric gravity waves at ionospheric heights, *Can. J. Phys.*, *38*, 1441–1481, 1960.

Holton, J.R., The role of gravity wave induced drag and diffusion in the momentum budget of the mesosphere, *J. Atmos. Sci.*, *39*, 791–799, 1982.

Holton, J.R., The influence of gravity wave breaking on the general circulation of the middle atmosphere, *J. Atmos. Sci.*, *40*, 2497–2507, 1983.

Holton, J.R., and W.M. Wehrbein, A numerical model of the zonal mean circulation of the middle atmosphere, *Pageoph.*, *118*, 284–306, 1980.

Labitzke, K.G., and H. van Loon, *The Stratosphere*, 179 pp., Springer-Verlag, Berlin, 1999.

Leovy, C., Simple models of thermally driven mesospheric circulation, *J. Atmos. Sci.*, *21*, 327–341, 1964.

Le Texier, H., S. Solomon, and R.R. Garcia, Seasonal variability of the OH Meinel bands, *Planet. Space Sci.*, *35*, 977–989, 1987.

Lindzen, R.S., Thermally driven diurnal tide in the atmosphere, *Quart. J. R. Meteorol. Soc.*, *93*, 18–42, 1967.

Lindzen, R.S., Turbulences and stress owing to gravity wave and tidal breakdown, *J. Geophys. Res.*, *86*, 9707–9714, 1981.

Lübken, F.-J., and U. von Zahn, Thermal structure of the mesopause region at polar latitudes, *J. Geophys. Res.*, *96*, 20841–20857, 1991.

Manson, A., et al., Seasonal variations of the semidiurnal and diurnal tides in the MLT: multi-year MF radar observations from 2 to 70 N, and the GSWM tidal model, *J. Atmos. Solar-Terr. Phys.*, *61*, 809–828, 1999.

Megie, G., Laser Measurements of Atmospheric Trace Constituents, in *Laser Remote Chemical Analysis*, edited by R.M. Measures, pp. 333, John Wiley & Sons, New York, NY, 1988.

Meriwether, J.W., X. Gao, V.B. Wickwar, T.D. Wilkerson, K.C. Beissner, S.C. Collins, and M.E. Hagan, Observed coupling of the mesosphere inversion layer to the thermal tidal structure, *Geophys. Res. Lett.*, *25*, 1479–1482 & 2127, 1998.

Murgatoyd, R.J., Winds and temperatures between 20 km and 100 km—A review, *Quart. J. Roy. Meteor. Soc., 83*, 417–458, 1957.

Nastrom, G.D., and D.C. Fritts, Sources of mesoscale variability of gravity waves. Part I: Topographic excitation, *J. Atmos. Sci., 49*, 101–110, 1992.

Nelson, K.L.M., Lidar Observations of Oscillations in the Middle Atmosphere, MS thesis, Utah State University, Logan, 2003.

Neuber, R., P.v.d. Gathen, and U.von Zahn, Altitude and temperature of the mesopause at 69° N latitude in winter, *J. Geophys. Res., 93*, 11093–11101, 1988.

Plane, J.M.C., C.S. Gardner, J. Yu, C.Y. She, R.R. Garcia, and H.C. Pumphrey, Mesospheric Na layer at 40°N: Modeling and observations, *J. Geophys. Res., 104* (D3), 3773–3788, 1999.

Rassoul, H.K., R.P. Rorhbaugh, B.A. Tinsley, and D.W. Slater, Spectrometric and photometric observations of low-latitude aurorae, *J. Geophys. Res., 98*, 7695, 1993.

Rees, M.H., and R.G. Roble, Observations and theory of the formation of stable auroral red arcs, *Rev. Geophys. Space Phys., 13*, 201-242, 1975.

Schoeberl, M.R., and D.F. Strobel, The Zonally Averaged Circulation of the Middle Atmosphere, *J. Atmos. Sci., 35*, 577–591, 1978.

Senft, D.C., G.C. Papen, C.S. Gardner, J.R. Yu, D.A. Krueger, C.Y. She, Seasonal variations of the thermal structure of the mesopause region at Urbana, IL (40°N, 88°W), and Fort Collins, CO (41°N, 105°W), *Geophys. Res. Lett., 21*, 821–824, 1994.

She, C.Y., and U. von Zahn, Concept of a two-level mesopause: Support through new lidar observations, *J. Geophys. Res., 103*, 5855–5863, 1998.

She, C.Y., J.R. Yu, H. Chen, Observed thermal structure of a midlatitude mesopause, *Geophys. Res. Lett., 20*, 567–570, 1993.

She, C.Y., S. Chen, Z. Hu, J.Sherman, J.D. Vance, V. Vasoli, M.A. White, J. Yu, and D.A. Krueger, Eight-year climatology of nocturnal temperature and sodium density in the mesopause region (80–105 km) over Fort Collins, CO (41°N, 105°W), *Geophys. Res. Lett., 27*, 3289–3292, 2000.

Sica, R.J., S. Sargoytchev, P.S. Argall, E.F. Borra, L. Girard, C.T. Sparrow, and S. Flatt, Lidar measurements taken with a large-aperture liquid mirror. 1. Rayleigh-scatter system, *Appl. Optics, 34* (30), 6925–6936, 1995.

States, R.J., and C.S. Gardner, Thermal structure of the mesopause region (80–105 km) at 40°N latitude. Part I: Seasonal Variations, *J. Atmos. Sci., 57*, 2000a.

States, R.J., and C.S. Gardner, Thermal structure of the mesopause regioin (80–105 km) at 40°N latitude. Part II: Diurnal Variations, *J. Atmos. Sci., 57*, 78–92, 2000b.

Tao, X., and C.S. Gardner, Heat flux observations in the mesopause region above Haleakala, *Geophys. Res. Lett., 22*, 2829–2832, 1995.

Taylor, M.J., D.N. Turnbull, and R.P. Lowe, Spectrometric and imaging measurements of a spectacular gravity wave event observed during the ALOHA-93 campaign, *Geophys. Res. Lett., 22*, 2848–2852, 1995.

Thomas, G.E., Global change in the mesophere-lower thermosphere region: has it already arrived?, *J. Atmos. Terr. Phys., 58*, 1629–1656, 1996.

Tsuda, T., Y. Murayama, T. Nakamura, R.A. Vincent, A.H. Manson, C.E. Meek, and R.L. Wilson, Variations of the gravity wave characteristics with height, season and latitude revealed by comparative observations, *J. Atmos. Terr. Phys., 56*, 555–568, 1994.

von Zahn, U., and J. Höffner, Mesopause temperature profiling by potassium lidar, *Geophys. Res. Letts., 23*, 141–144, 1996.

von Zahn, U., J. Höffner, V. Eska, and M. Alpers, The mesopause altitude: Only two distinctive levels worldwide?, *Geophs. Res. Lett., 23*, 3231–3234, 1996.

Whiteway, J.A., A.I. Carswell, and W.E. Ward, Mesospheric temperature inversions with overlying nearly adiabatic lapse rate: an indication of a well-mixed turbulent layer, *Geophys. Res. Lett., 22* (10), 1201-1204, 1995.

Wickwar, V.B., M.J. Taylor, J.P. Herron, and B.A. Martineau, Visual and lidar observations of noctilucent clouds above Logan, Utah, at 41.7°N, *J. Geophys. Res., 107* (D7), 10.1029/2001JD001180, 2002.

Wickwar, V.B., T.D. Wilkerson, M. Hammond, and J.P. Herron, Mesospheric temperature observations at the USU / CASS Atmospheric Lidar Observatory (ALO), in *Remote Sensing of the Atmosphere, Environment, and Space*, pp. 272–284, SPIE, Sendai, Japan, 2000.