

WATER VAPOR PROFILING USING A WIDELY TUNABLE AMPLIFIED  
DIODE LASER DIFFERENTIAL ABSORPTION LIDAR (DIAL)

by

Michael Drew Obland

A dissertation submitted in partial fulfillment  
of the requirements for the degree

of

Doctor of Philosophy

in

Physics

MONTANA STATE UNIVERSITY  
Bozeman, Montana

April 2007

©COPYRIGHT by  
Michael Drew Obland  
2007  
All Rights Reserved

APPROVAL  
of a dissertation submitted by  
Michael Drew Obland

This dissertation has been read by each member of the dissertation committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the Division of Graduate Education.

Dr. Joseph A. Shaw

Dr. John L. Carlsten

Approved for the Department of Physics

Dr. William A. Hiscock

Approved for the Division of Graduate Education

Dr. Carl A. Fox

## STATEMENT OF PERMISSION TO USE

In presenting this dissertation in partial fulfillment of the requirements for a doctoral degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. I further agree that copying of this dissertation is allowable only for scholarly purpose, consistent with "fair use" as prescribed in the U.S. Copyright Law. Requests for extensive copying or reproduction of this dissertation should be referred to Bell & Howell Information and Learning, 300 North Zeeb Road, Ann Arbor, Michigan 48106, to whom I have granted "the exclusive right to reproduce and distribute my dissertation in and from microform along with the non-exclusive right to reproduce and distribute my abstract in any format in whole or in part."

Michael Drew Obland

April 2007

To my family,

Thank you for teaching me that I can do anything that I set my mind to, and for making this all possible with your unfailing guidance, support, and sacrifice through the many years it took to achieve this dream.

To my friends,

Thank you for your unselfish understanding and support through all of the Friday and Saturday nights when I was too busy studying, working, or running experiments to hang out.

I could not have done this without you. To you, I dedicate this dissertation.

## ACKNOWLEDGMENTS

“If I have seen a little further it is by standing on the shoulders of Giants.” - Sir Isaac Newton

Thank you to my co-chairs, Dr. Joe Shaw and Dr. John Carlsten, for the opportunity to do this work and for being so much fun to work for. Thank you for teaching me, for leading me to find my own answers, for patiently answering my many, many questions, and for giving me space to find my own path. Dr. Kevin Repasky, thank you for your patience and uncanny ability for getting hardware to work. Thank you for putting your students (including me) first and for being a leading example of how the education system should work. Dr. Dave Klumpar, thank you for the many satellite adventures we have had over the years, and for putting your faith and the fate of a grand project like Montana’s first satellite in the hands of someone who really had no idea what he was doing! Dr. Bill Hiscock, thank you for bringing me to MSU, and for your ceaseless support of anything I wanted to do to further my education. Above all, thank you to all of you for not only being mentors, but for being friends. Thank you to: the Physics Department staff, Margaret Jarret, Jeannie Gunderson, Rose Waldon, Glenda Winslow, Sarah Barutha, Jeremy Gay, and Norm Williams; Wilma Ang and Muriel Holmquist in the Electrical and Computer Engineering department; Dale Huls in the MSU Office of Sponsored Programs; the Montana Space Grant Consortium and Clarice Koby; NASA and the NASA Graduate Student Researchers Program for supporting my research; my NASA mentors, Dr. Jonathan A. R. Rall, Mr. Joe Kujawski, and Dr. Doug O’Handley; the students of the Space Science and Engineering Laboratory (SSEL), especially Dr. Brian Larsen; Dr. Lei Meng, Dr. Gregg Switzer, and the students of the Optical Remote Sensor Laboratory, especially Nathan Seldomridge, Dr. Nathan Pust, Amin Nehrir, and Nick Jurich.

## TABLE OF CONTENTS

|                                                                                  |    |
|----------------------------------------------------------------------------------|----|
| 1. INTRODUCTION . . . . .                                                        | 1  |
| The Importance of Atmospheric Water Vapor Monitoring . . . . .                   | 1  |
| Using Lidar to Measure Atmospheric Water Vapor . . . . .                         | 2  |
| The Montana State University Water Vapor Differential Absorption Lidar . . . . . | 6  |
| 2. THEORY . . . . .                                                              | 8  |
| Earth's Atmosphere . . . . .                                                     | 8  |
| Remote Sensing With Lidar . . . . .                                              | 8  |
| The Lidar Equation . . . . .                                                     | 12 |
| Radiometric Derivation of the Lidar Equation . . . . .                           | 13 |
| Full Overlap . . . . .                                                           | 14 |
| Partial Overlap . . . . .                                                        | 16 |
| Comparison With the Lidar Equation . . . . .                                     | 18 |
| DIAL Equation Derivation . . . . .                                               | 21 |
| 3. HORIZONTAL TUNING EXPERIMENTS . . . . .                                       | 24 |
| Introduction . . . . .                                                           | 24 |
| Steam Tunnel Experiments . . . . .                                               | 25 |
| Roofport Experiments . . . . .                                                   | 28 |
| System Description . . . . .                                                     | 28 |
| External Cavity Diode Laser (ECDL) . . . . .                                     | 31 |
| Tapered Amplifier . . . . .                                                      | 36 |
| Acousto-optic Modulator (AOM) . . . . .                                          | 41 |
| Reference Power Meters and Beam Splitter . . . . .                               | 43 |
| Telescope . . . . .                                                              | 44 |
| Narrowband Filter . . . . .                                                      | 45 |
| Avalanche Photodiode (APD) Detector . . . . .                                    | 46 |
| Multi-channel Scalar (MCS) . . . . .                                             | 48 |
| Targets . . . . .                                                                | 49 |
| System Diagnostics . . . . .                                                     | 49 |
| P/I Curves . . . . .                                                             | 50 |
| Linewidth and Tuning . . . . .                                                   | 51 |
| Reference Power Measurements . . . . .                                           | 52 |
| CW Measurements . . . . .                                                        | 55 |
| Preliminary Pulsed Measurements . . . . .                                        | 58 |
| Pulsed Measurements . . . . .                                                    | 60 |
| Conclusions . . . . .                                                            | 61 |
| 4. WATER VAPOR ABSORPTION LINE SELECTION . . . . .                               | 64 |
| Theory . . . . .                                                                 | 64 |

|                                                                                                              |     |
|--------------------------------------------------------------------------------------------------------------|-----|
| Line Selection Criteria . . . . .                                                                            | 65  |
| Temperature Sensitivity . . . . .                                                                            | 65  |
| Optical Depth . . . . .                                                                                      | 74  |
| Nearby Absorption Features . . . . .                                                                         | 79  |
| Line Selection . . . . .                                                                                     | 79  |
| 5. DIAL SYSTEM AND EXPERIMENT . . . . .                                                                      | 81  |
| Introduction . . . . .                                                                                       | 81  |
| Design . . . . .                                                                                             | 81  |
| System Description . . . . .                                                                                 | 84  |
| Cascaded Tapered Amplifiers . . . . .                                                                        | 88  |
| Multi-channel Scalar Card . . . . .                                                                          | 91  |
| Narrowband Filter . . . . .                                                                                  | 92  |
| Extended Tuning System . . . . .                                                                             | 93  |
| Data Acquisition and Analysis Software . . . . .                                                             | 100 |
| Testing . . . . .                                                                                            | 101 |
| Noise and Background Signal Levels . . . . .                                                                 | 101 |
| Beam Shape . . . . .                                                                                         | 103 |
| Spectral Purity . . . . .                                                                                    | 104 |
| P/I Curves . . . . .                                                                                         | 113 |
| Linewidth and Tuning . . . . .                                                                               | 114 |
| On- and Off-line Tuning Characterization . . . . .                                                           | 116 |
| Absorption Cell Measurements . . . . .                                                                       | 119 |
| Reference Power . . . . .                                                                                    | 124 |
| Data Runs . . . . .                                                                                          | 125 |
| 6. CONCLUSION . . . . .                                                                                      | 137 |
| REFERENCES . . . . .                                                                                         | 142 |
| APPENDICES . . . . .                                                                                         | 149 |
| APPENDIX A: PRELIMINARY LIDAR EXPERIMENTS . . . . .                                                          | 150 |
| APPENDIX B: MAXIMUM PERMISSABLE EXPOSURE (MPE) LIMITS<br>AND FEDERAL AVIATION ADMINISTRATION (FAA) APPROVALS | 168 |
| APPENDIX C: DIAL OPERATING GUIDE . . . . .                                                                   | 180 |
| APPENDIX D: LIST OF ACRONYMS . . . . .                                                                       | 187 |

## LIST OF TABLES

| Table |                                                                                                                                                                                                                                                 | Page |
|-------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 3.1   | Estimated pathlengths needed to obtain measurable absorptions due to water vapor in the atmosphere for three candidate water vapor absorption lines within tuning range of MSU ECDL's, ordered left to right from strongest to weakest. . . . . | 25   |
| 4.1   | Values for $E''$ , $\alpha$ , and $\gamma_L$ as determined by the linear fit of Figure 4.1.                                                                                                                                                     | 69   |
| 4.2   | Optical Depth values for the water vapor absorption line centered at $12074.5689\text{ cm}^{-1}$ using a custom MATLAB analysis and HiTRAN-PC simulation. . . . .                                                                               | 78   |
| 5.1   | Laser transmitter requirements for water-vapor DIAL measurements with an error due to individual laser properties of $< 3\%$ compared to the Montana State University DIAL transmitter specifications. . . . .                                  | 89   |
| 5.2   | Ordering specifications for the narrowband filter. . . . .                                                                                                                                                                                      | 94   |
| 5.3   | Results of testing for background light leakage into the APD. . . . .                                                                                                                                                                           | 103  |
| A.1   | A comparison between the simulated and measured amplifier output powers for Construct 1 at the wavelengths of 1064.6 nm and 975 nm. . . . .                                                                                                     | 160  |
| A.2   | A comparison between the simulated and measured amplifier output powers for Construct 2 at the wavelength of 1064.6 nm. . . . .                                                                                                                 | 163  |
| A.3   | A comparison between the simulated and measured amplifier output powers for Construct 3 in different configurations at the wavelength of 1064.6 nm. . . . .                                                                                     | 164  |
| B.4   | Contact information for the FAA that I used in 2004. . . . .                                                                                                                                                                                    | 172  |
| B.5   | Contact information for the FAA, current as of February, 2007. . . . .                                                                                                                                                                          | 172  |
| B.6   | Specifications of the FAA's four flight zones. ( <i>*Note that minimum altitude requirements for these irradiance levels also apply.</i> NM=Nautical Mile) . . . . .                                                                            | 173  |

|     |                                                                       |     |
|-----|-----------------------------------------------------------------------|-----|
| B.7 | Values used for the maximum permissible exposure calculations. . . .  | 174 |
| B.8 | Contact information for the CDRH. . . . .                             | 177 |
| B.9 | Contact information for airports in Bozeman and Salt Lake City, Utah. | 178 |

## LIST OF FIGURES

| Figure |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | Page |
|--------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
| 2.1    | Schematics of Earth's atmospheric layers and composition. Images courtesy of NASA<br>( <a href="http://liftoff.msfc.nasa.gov/academy/space/atmosphere.html">http://liftoff.msfc.nasa.gov/academy/space/atmosphere.html</a> ). . . . .                                                                                                                                                                                                                                                                                                                                                                                                | 9    |
| 2.2    | A cartoon outline of the basic principle behind lidar. See the text for a detailed explanation of each step. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | 11   |
| 2.3    | The most basic lidar configuration, consisting of a transmitting laser, a scattering target, and a receiving telescope. The transmitted beam laser is depicted with solid lines, while the telescope FOV is shown with dotted lines. . . . .                                                                                                                                                                                                                                                                                                                                                                                         | 15   |
| 2.4    | Partial overlap of the transmitted beam area (solid lines) with the receiver's FOV (dotted lines). . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 17   |
| 3.1    | A picture of the steam tunnel experiment. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 27   |
| 3.2    | A schematic diagram of the horizontal tuning experiment. A tunable ECDL is coupled into a tapered flared amplifier. The amplified output is sent out into the atmosphere and a 28-cm telescope is used to collect the backscattered light. The light collected by the telescope is measured using an avalanche photodiode operating in the Geiger mode. . . . .                                                                                                                                                                                                                                                                      | 29   |
| 3.3    | A plot showing absorption features of atmospheric constituents of current scientific interest in the visible and near-infrared optical spectrum, compared to the availability of diodes with wavelengths in this region. . . . .                                                                                                                                                                                                                                                                                                                                                                                                     | 32   |
| 3.4    | A schematic of a tunable external cavity diode laser in a Littman-Metcalf configuration. The collimated light from a laser diode is incident on the diffraction grating. The zeroth order reflection is used as the output from the external cavity laser while the first order reflection is used to spatially separate the spectral output from the diode. The prism serves as a retroreflector to provide optical feedback to the diode laser via a second reflection from the diffraction grating and is used to control the operating frequency of the external cavity laser. Tuning is achieved by rotating the prism. . . . . | 34   |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                           |    |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.5  | A picture of an ECDL built at Montana State University. This laser can be tuned from 824 nm to 841 nm. . . . .                                                                                                                                                                                                                                                                                                                            | 35 |
| 3.6  | A picture of the Sacher Lasertechnik TA830 tapered amplifier. The input mirror used for seeding the TA is visible in the center of the picture. The collimating optics are on the far left. . . . .                                                                                                                                                                                                                                       | 37 |
| 3.7  | A picture of the Sacher Lasertechnik Pilot driver used to control the tapered amplifier in the horizontal tuning experiments. . . . .                                                                                                                                                                                                                                                                                                     | 38 |
| 3.8  | A plot of the tuning of the laser system. This is shown by three overlaid plots of the optical power of the injection seeded amplifier (attenuated to avoid damaging the OSA). The ECDL was tuned mechanically by adjusting the retroreflective prism to 824 nm (832 nm, 841 nm) and was used to seed the amplifier. The spectral output of the amplifier is controlled by the spectral properties of the injection seeded ECDL laser. 38 |    |
| 3.9  | A plot of the horizontal path transmission calculated using HiTRAN-PC through a 1 km path length as a function of wavelength accessible by the tunable ECDL shown in figure 3.8. The absorption features are due to water vapor. . . . .                                                                                                                                                                                                  | 39 |
| 3.10 | A plot of the pulsing characteristics of the Sacher Lasertechnik tapered amplifier. Faster pulses also have reduced output amplitudes, disappearing almost completely below 4 $\mu s$ , much too slow for use in the DIAL system. . . . .                                                                                                                                                                                                 | 41 |
| 3.11 | A picture of the acousto-optic modulator (AOM) used to pulse the cw laser beam. The entrance aperture is visible on the side, below the “5” in 1205C-2. . . . .                                                                                                                                                                                                                                                                           | 42 |
| 3.12 | A plot of the pulsing characteristics of the AOM. Note the very clean square-wave shape of the output pulses. . . . .                                                                                                                                                                                                                                                                                                                     | 42 |
| 3.13 | A picture of broadband beam samplers. Image courtesy of Newport.com ( <a href="http://www.newport.com">http://www.newport.com</a> ). . . . .                                                                                                                                                                                                                                                                                              | 43 |
| 3.14 | A picture of the Newport 1830c (top) and 1930c (bottom), used for diagnostics and reference power measurements in the horizontal tuning and vertical DIAL experiments. . . . .                                                                                                                                                                                                                                                            | 44 |

|      |                                                                                                                                                                                                                                  |    |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.15 | A schematic of a Schmidt-Cassegrain telescope. Image courtesy of Celestron.com ( <a href="http://www.celestron.com">http://www.celestron.com</a> ).                                                                              | 45 |
| 3.16 | A transmission plot for the “Starbright” coating on the telescope used in the horizontal lidar tuning experiments. Image courtesy of Celestron.com ( <a href="http://www.celestron.com">http://www.celestron.com</a> ).          | 46 |
| 3.17 | A picture of the type of narrowband filter used in the horizontal tuning experiments.                                                                                                                                            | 47 |
| 3.18 | A picture of the avalanche photodiode (APD) detector.                                                                                                                                                                            | 48 |
| 3.19 | A picture of the Stanford Research Systems Multi-channel Scalar (MCS) with display screen used in the horizontal tuning experiments.                                                                                             | 49 |
| 3.20 | A picture of the three hard targets and their ranges used in the horizontal tuning experiments, taken from the roof of Cobleigh Hall at Montana State University, just above the roofport room where the measurements were made. | 49 |
| 3.21 | Early results from the horizontal tuning experiments. The data should show a water vapor absorption line centered at 829.022 nm with the counts rising to a steady value in the wings of the line.                               | 50 |
| 3.22 | P/I curves for the ECDL and TA used in the horizontal tuning experiments.                                                                                                                                                        | 51 |
| 3.23 | Optical spectrum analyzer traces for the ECDL and TA used in the horizontal tuning experiments.                                                                                                                                  | 52 |
| 3.24 | A plot of the ratio output wavelength of the amplifier to the output wavelength of the ECDL. The wavelengths agree to within the error of the wavemeters.                                                                        | 53 |
| 3.25 | A plot showing the power modes of the tapered amplifier. As the ECDL tunes, the power output of the TA changes drastically, necessitating normalization of the return data with transmit power.                                  | 54 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |    |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.26 | A plot showing how the reference power measurement actually tracks the transmit power of the horizontal system. Note that the Newport 1830c is more accurate. . . . .                                                                                                                                                                                                                                                                                                                                       | 55 |
| 3.27 | A plot of the transmission through the atmosphere as a function of wavelength near 829.02 nm. The closed (open) circles represent measurements made for a 1.71 km (0.35 km) path length. The solid (dashed) line is a theoretical calculation using HiTRAN-PC with the measured temperature and humidity used in the modeling. . . . .                                                                                                                                                                      | 57 |
| 3.28 | A plot of the transmission through the atmosphere as a function of wavelength near 831.62 nm. The closed circles represent measurements made for a 1.67 km path length. The solid line is a theoretical calculation using HiTRAN-PC with the measured temperature and humidity used in the modeling. . . . .                                                                                                                                                                                                | 58 |
| 3.29 | A plot of the atmospheric transmission as a function of wavelength. The open circles represent measurements made with a cw laser transmitter while the filled circles represent measurements made with a pulsed laser transmitter. The solid line represents the results of a HiTRAN-PC calculation for a 1.67 km horizontal path calculation. . .                                                                                                                                                          | 59 |
| 3.30 | A plot of the relative transmission through the atmosphere as a function of wavelength near 829.022 nm. The open (closed) circles represent measurements made for a 0.35 km (1.71 km) path length. The solid and dashed lines are theoretical calculations using HiTRAN-PC with the measured temperature, humidity, and path length. . . . .                                                                                                                                                                | 62 |
| 3.31 | A plot of the relative transmission through the atmosphere as a function of wavelength near 831.850 nm. The open (closed) circles represent measurements made for a 0.35 km (1.67 km) path length. The solid and dashed lines are theoretical calculations using HiTRAN-PC with the measured temperature, humidity, and path length. . . . .                                                                                                                                                                | 63 |
| 4.1  | The top graphs are Figures 2 and 3 from <i>Browell et al.</i> (1991) showing linear fit relationships between the linewidth temperature dependence parameter $\alpha$ , the Lorentz linewidth $\gamma_L$ , and the ground state energy $E''$ in the 720 nm region. These graphs are repeated here to show consistency between my method and that of <i>Browell et al.</i> (1991). The bottom graphs show the linear fit relationships between these same parameters in the 824 nm to 841 nm region. . . . . | 70 |

|     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |    |
|-----|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.2 | The MATLAB integration function could not solve the Voigt integral at low temperatures, sending the value of the integral to zero at a certain point. A custom integration method needed to be written to solve the integral down to 100 $K$ . . . . .                                                                                                                                                                                                                                                                                                    | 71 |
| 4.3 | These figures show the number density error produced across a range of temperatures, pressures, and $E''$ values, generated using my MATLAB Voigt profile calculator. They are nearly identical to Figures 4 and 5 from <i>Browell et al.</i> (1991), showing that the calculation method is valid. The top left graph shows the number density temperature sensitivity on a larger scale. The other graphs show the number density temperature sensitivity at 1.0 $atm$ , 0.5 $atm$ , and 0.25 $atm$ pressures scaled to a $\pm 0.10\%/K$ error. . . . . | 72 |
| 4.4 | These figures show the mixing ratio error produced across a range of temperatures, pressures, and $E''$ values, generated using my MATLAB Voigt profile calculator. They are nearly identical to Figure 6 from <i>Browell et al.</i> (1991). The top left graph shows the mixing ratio temperature sensitivity on a larger scale. The other graphs show the mixing ratio temperature sensitivity at 1.0 $atm$ , 0.5 $atm$ , and 0.25 $atm$ pressures scaled to a $\pm 0.10\%/K$ error. . . . .                                                            | 73 |
| 4.5 | Deviation from the Voigt profile in the number density error calculations at 1.0 $atm$ that would occur if a Lorentz profile were used. . . .                                                                                                                                                                                                                                                                                                                                                                                                             | 74 |
| 4.6 | Deviation from the Voigt profile in the number density error calculations at 0.25 $atm$ that would occur if a Lorentz profile were used. . . .                                                                                                                                                                                                                                                                                                                                                                                                            | 75 |
| 4.7 | The average monthly water vapor density in Bozeman, Montana. The water vapor density was calculated using temperature, pressure, and relative humidity data collected by the Optical Remote Sensor Laboratory's weather station on the roof of Cobleigh Hall at Montana State University between August 2005 and July 2006. . . . .                                                                                                                                                                                                                       | 77 |
| 4.8 | A HiTRAN-PC plot at default values of 1 $atm$ and 296 $K$ across a 1.5 $km$ horizontal path length, showing all absorption lines between 12059.8167 $cm^{-1}$ and 12086.0527 $cm^{-1}$ (829.2-827.4 $nm$ ). The final on- and off-line wavelengths selected for the water vapor DIAL are indicated. 80                                                                                                                                                                                                                                                    |    |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.1  | A plot of the maximum allowable error in pointing a bistatic laser beam to keep it within the field of view of the detector, as a function of altitude. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 85  |
| 5.2  | A plot produced by Zemax showing the design for the DIAL receiver.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | 87  |
| 5.3  | A plot of the reflection for the Thorlabs E03 coating, used in all of the mirrors in the DIAL system. Image courtesy of Thorlabs.com. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 89  |
| 5.4  | A picture of the Sacher Lasertechnik Pilot driver used to control the cascaded tapered amplifier in the vertical DIAL experiments. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 92  |
| 5.5  | A plot of the DIAL's target water vapor absorption line at 828.187 nm (vacuum wavelength, $n = 1.0$ ) using HiTRAN-PC. The wavelength shift due to two values of the index of refraction of air is shown. A value of $n = 1.00022$ was calculated internally by the Burleigh wavemeter using ambient temperature and relative humidity measurements. A value of $n = 1.0002896$ was calculated using Cauchy's formula. The red box signifies a hypothetical rectangular band pass region of a 250 pm narrowband filter centered at 828.0069 nm, the line center location using the wavemeter index of refraction. . . . . | 94  |
| 5.6  | A plot showing the transmission curve for the narrowband filter, with the DIAL on-line (828.0069 nm) and off-line (828.1069 nm) labeled. Data for the transmission was provided courtesy of Barr Associates. . . . .                                                                                                                                                                                                                                                                                                                                                                                                      | 95  |
| 5.7  | A schematic of the extended tuning system for the ECDL. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 97  |
| 5.8  | A schematic of the gas absorption cell experimental setup. Note that the laser makes 36 passes within the gas absorption cell for a total path length of 19.8 meters. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                             | 99  |
| 5.9  | A picture of the DIAL instrument in its operational form inside the roofport room of Cobleigh Hall. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | 102 |
| 5.10 | A BeamView figure showing the intensity of the ECDL beam after traveling through the anamorphic prism pair, optical isolators, half wave plate, and PBS cube. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                     | 104 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |     |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.11 | These BeamView figures show the tapered amplifier beam shape at 3 different distances from the amplifier, unseeded (left column) and seeded by the ECDL (right column). The top row is at a distance of 5 inches, the middle row is at a distance of 10 inches, and the bottom row is at a distance of 30 inches. The red lines are cross sections of the intensity in two dimensions. The yellow ellipse shows the ellipticity of the beam. Notice that the beam is much more uniform when seeded by the ECDL, and becomes more circular as it propagates. . . . . | 105 |
| 5.12 | A plot of a water vapor absorption line at low pressure (high altitude) or at high pressure, such as in a pressurized multi-pass, gas absorption cell. A hypothetical Gaussian laser line with a 40 MHz linewidth is overplotted for comparison. *See <i>Wulfmeyer</i> , 1998 for a description of using a multi-pass gas absorption cell for making spectral purity measurements. . . . .                                                                                                                                                                          | 107 |
| 5.13 | A linear plot of the power output of the DIAL transmitter with a narrowband filter in place, measured before and after the AOM through a multi-mode fiber on an OSA. . . . .                                                                                                                                                                                                                                                                                                                                                                                        | 109 |
| 5.14 | These OSA traces show that the ASE structure in the DIAL transmitter output is relatively independent of the type of fiber used to make the measurement, as the structure is similar before (left) and after (right) the AOM for both single-mode and multi-mode fibers. . . . .                                                                                                                                                                                                                                                                                    | 109 |
| 5.15 | These OSA traces show that the ASE structure in the DIAL transmitter output is relatively independent of the presence of the AOM. The structure is similar before and after the AOM for both multi-mode (top row) and single-mode (bottom row) fibers, with (right column) or without (left column) a narrowband filter in place. . . . .                                                                                                                                                                                                                           | 111 |
| 5.16 | These OSA traces show that the ASE structure in the DIAL transmitter output is relatively independent of the length of fiber optic cable being used. The structure is similar before (left column) and after (right column) the AOM for both multi-mode (top row) and single-mode (bottom row) fibers, with and without a narrowband filter in place and for varying fiber lengths. . . . .                                                                                                                                                                         | 112 |
| 5.17 | OSA traces showing the effect of using a narrow band filter in the receiver of the DIAL. The spectral purity is drastically improved. . .                                                                                                                                                                                                                                                                                                                                                                                                                           | 113 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |     |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.18 | The latest P/I curve for the ECDL is plotted against the P/I curve performed almost a year earlier during the horizontal tuning experiments described in Chapter 3. Aging of the diode is evident as it requires more current to reach the same power output. . . . .                                                                                                                                                                                                                              | 114 |
| 5.19 | P/I curves for the two amplifiers used in the DIAL experiment. Notice the large difference between amplifiers seeded, but not saturated, and seeded at nearly full seed power. . . . .                                                                                                                                                                                                                                                                                                             | 115 |
| 5.20 | An OSA trace of the ECDL output, showing its narrow linewidth and large sidemode suppression. . . . .                                                                                                                                                                                                                                                                                                                                                                                              | 115 |
| 5.21 | OSA traces of the outputs of the DIAL amplifiers. The large increase in amplified spontaneous emission due to higher drive current and seed power for the second amplifier is prominent, but disappears as expected when the amplifier is seeded properly. . . . .                                                                                                                                                                                                                                 | 116 |
| 5.22 | A ratio of the laser wavelength measured after the AOM and after the ECDL, showing that the wavelengths agree. . . . .                                                                                                                                                                                                                                                                                                                                                                             | 117 |
| 5.23 | A plot of tuning time necessary to lock the laser system to the on-line wavelength, for different initial starting PZT voltage settings, and hence starting wavelengths, of the laser. . . . .                                                                                                                                                                                                                                                                                                     | 118 |
| 5.24 | A plot showing stable on- and off-line tuning of the laser system at approximately one-hour intervals over a span of five hours. . . . .                                                                                                                                                                                                                                                                                                                                                           | 119 |
| 5.25 | An expanded view of the second segment of Fig. 5.24 displaying the computer-controlled feedback loop of the laser system, fine-tuning and holding the laser output to the on-line wavelength, 828.187 nm. . . .                                                                                                                                                                                                                                                                                    | 120 |
| 5.26 | A plot of the water vapor number density in the absorption cell compared to the number density in the atmosphere as measured by a weather station on the roof of the building where the absorption cell measurements were performed. Notice that the number density within the absorption cell is always higher than that of the atmosphere due to the presence of the liquid water reservoir connected to the cell. The effect of adding humid air to the absorption cell can be easily seen. . . | 121 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                |     |
|------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.27 | A plot of the normalized power transmitted through the 19.8 meter path length of the gas absorption cell. Absorption by water vapor molecules within the cell is responsible for the reduced on-line signal.                                                                                                                                                                                   | 122 |
| 5.28 | A plot of the relative transmission through the gas absorption cell as a function of wavelength. The closed circles represent measurements made by the laser system. The solid line is a theoretical prediction of the absorption by water vapor in the absorption cell using HiTRAN-PC with the <i>in situ</i> measurements of temperatures and humidity. . . . .                             | 124 |
| 5.29 | Reference power test measurements showing the relaxation effect of the AOM on the left and the difference between pulsed and cw measurements of reference power on the right. . . . .                                                                                                                                                                                                          | 126 |
| 5.30 | An example of initial DIAL data runs, in which the saturation and afterpulse of the APD is apparent, and the striping effect caused by the AOM can be seen. . . . .                                                                                                                                                                                                                            | 127 |
| 5.31 | The high-count correction factor for the APD detector. Data is courtesy of Perkin-Elmer. . . . .                                                                                                                                                                                                                                                                                               | 129 |
| 5.32 | Example DIAL data in which the background and afterpulsing effects were attempted to be removed, without success. . . . .                                                                                                                                                                                                                                                                      | 129 |
| 5.33 | Evidence of alignment of the transmit beam with the receiver FOV. The initial laser pulse is 75 meters wide while the flash seen by the detector is over 225 meters wide, indicating return from atmospheric molecules and particles in the near field. Clouds can be seen at about 2.4 km altitude and decrease to about 1.8 km above the ground at the conclusion of the experiment. . . . . | 131 |
| 5.34 | Time-averaged raw counts (right) and background-subtracted counts (left) showing the initial laser pulse, atmospheric returns, and cloud returns. . . . .                                                                                                                                                                                                                                      | 132 |
| 5.35 | A comparison between a radiosonde launched at MSU and one launched in Great Falls around the same time. . . . .                                                                                                                                                                                                                                                                                | 133 |

|      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |     |
|------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.36 | A comparison of an aligned (01/09/07) transmit beam and an unaligned (01/18/07) transmit beam. The left graph shows time-averaged on-line counts and the right graph shows time-averaged off-line counts. Notice the steep falloff in the unaligned (green) beam after the initial laser pulse, whereas the aligned (red) beam is considerably longer due to atmospheric returns. The spike above 1500 meters is probably due to multiple scattering of the laser beam within the cloud. . . . . | 134 |
| 5.37 | A water vapor profile from the DIAL compared to a MSU radiosonde.                                                                                                                                                                                                                                                                                                                                                                                                                                | 135 |
| A.1  | Simulated output signal of the Ytterbium gain fiber versus length. . .                                                                                                                                                                                                                                                                                                                                                                                                                           | 157 |
| A.2  | A schematic of Construct 1. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 158 |
| A.3  | A schematic of Construct 2. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 158 |
| A.4  | A schematic of Construct 3. This schematic represents the final fiber optic laser amplifier design used for testing. . . . .                                                                                                                                                                                                                                                                                                                                                                     | 159 |
| A.5  | P-I curve for the seed laser. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                            | 160 |
| A.6  | Spectrum of the seed laser. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 161 |
| A.7  | P-I curve for the pump laser. A neutral density filter was used to obtain the data in pink. . . . .                                                                                                                                                                                                                                                                                                                                                                                              | 161 |
| A.8  | Spectrum of the pump laser. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 162 |
| A.9  | Simulated and measured ASE of Construct 2. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                               | 163 |
| A.10 | Simulated and measured results of the system. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                            | 165 |
| A.11 | Measured gain curve of the fiber amplifier. . . . .                                                                                                                                                                                                                                                                                                                                                                                                                                              | 166 |

## ABSTRACT

Water vapor is one of the most significant constituents of the atmosphere because of its role in cloud formation, precipitation, and interactions with electromagnetic radiation, especially its absorption of longwave infrared radiation. Some details of the role of water vapor and related feedback mechanisms in the Earth system need to be characterized better if local weather, global climate, and the water cycle are to be understood. Water vapor profiles are currently obtained with several remote sensing techniques, such as microwave radiometers, passive instruments like the Atmospheric Emitted Radiance Interferometer (AERI) and Atmospheric Infrared Sounder (AIRS), and Raman lidar. Each of these instruments has some disadvantage, such as only producing column-integrated water vapor amounts or being large, overly customized, and costly, making them difficult to use for deployment in networks or onboard satellites to measure water vapor profiles.

This thesis work involved the design, construction, and testing of a highly-tunable Differential Absorption Lidar (DIAL) instrument utilizing an all-semiconductor transmitter. It was an attempt to take advantage of semiconductor laser technology to obtain range-resolved water vapor profiles with an instrument that is cheaper, smaller, and more robust than existing field instruments. The eventual goal of this project was to demonstrate the feasibility of this DIAL instrument as a candidate for deployment in multi-point networks or satellite arrays to study water vapor flux profiles.

This new DIAL instrument transmitter has, for the first time in any known DIAL instrument, a highly-tunable External Cavity Diode Laser (ECDL) as a seed laser source for two cascaded commercial tapered amplifiers. The transmitter has the capability of tuning over a range of  $\sim 17$  nm to selectively probe several available water vapor absorption lines, depending on current environmental conditions. This capability has been called for in other recent DIAL experiments. Tests of the DIAL instrument to prove the validity of its measurements are presented. Initial water vapor profiles, taken in the Bozeman, MT, area, were taken, analyzed, and compared with co-located radiosonde measurements. Future improvements and directions for the next generation of this DIAL instrument are discussed.

## CHAPTER 1

## INTRODUCTION

The Importance of Atmospheric Water Vapor Monitoring

Water vapor plays an enormous role in Earth's atmospheric dynamics through cloud formation, precipitation, and interactions with electromagnetic radiation, especially its absorption of longwave infrared radiation (*Harries, 1997*). It is widely agreed that water vapor is one of the most important gasses in the atmosphere with regards to its role in local weather, global climate, and the water cycle. It is the primary driver of Earth's atmospheric heat engine and would have played a significant role on Mars if an environment suitable to the emergence of life ever developed there. Especially with the growing concern for understanding and predicting global climate change, detailed data of water vapor distribution and flux and related feedback mechanisms in the lowest 3 km of the troposphere, where most of the atmospheric water vapor resides, are required to aid in climate models (*Kington, 2000*). Radiosondes are the current standard method used to obtain routine water vapor profiles, but this technique can only provide information at one location at one point in time, is not very well distributed globally, and cannot easily be used to monitor the spatial and temporal changes of the water vapor concentrations (*Turner et al., 2000*). This has led to the exploration of passive and active remote sensing instruments for water vapor profile monitoring, such as microwave radiometers (*Han and Westwater, 1995*), passive instruments like the Atmospheric Emitted Radiance Interferometer (AERI) (*Feltz et al., 2003*) and Atmospheric Infrared Sounder (AIRS) (*Divakarla et al., 2006*),

and Raman LIDAR (*Turner et al.*, 2000). While each of these instruments shows great utility, they also all have some disadvantage, such as only producing column-integrated water vapor amounts or being large, overly customized, and costly, making them difficult to use for deployment in networks or onboard satellites to measure water vapor profiles. Improved capabilities to monitor range-resolved tropospheric water vapor profiles continuously in time at many locations are needed (*Rycroft*, 2000).

### Using Lidar to Measure Atmospheric Water Vapor

Light Detection and Ranging (Lidar) systems have been used to probe the atmosphere since shortly after the invention of the laser itself (*Schotland*, 1966). Lidars can be thought of as the optical equivalent to radars, since they actively illuminate the atmosphere with radiation (from a laser in the case of a lidar) and measure the subsequent scattered radiation. Many different types of lidars exist. Doppler lidars are used to infer atmospheric wind speeds based on Doppler shifting of the radiation scattered off of moving particles (*McGill et al.*, 1997; *Souprayen et al.*, 1999; *Gentry et al.*, 2000). High Spectral Resolution Lidar (HSRL) takes advantage of the differential spectral broadening of lighter air molecules compared to heavier aerosol particles to map and characterize aerosol types in the atmosphere (*Grund and Eloranta*, 1991; *Hair et al.*, 2001). Aerosol is a term used to describe dust, smoke, pollen, or generally anything in the atmosphere that is not “air”. Polarization lidars can be used to distinguish between ice and water clouds (*Sassen*, 1991; *Seldomridge et al.*, 2006), as well as for more novel uses such as detecting fish (*Churnside and Wilson*, 2004) and land mines (*Shaw et al.*, 2005).

Two other types of lidars have been used to retrieve water vapor profiles. Raman lidars can locate certain gasses by detecting the very faint characteristic Stokes-shifted

backscattered radiation caused by inelastic scattering. Differential Absorption Lidar (DIAL) is a technique that takes advantage of the differential absorption of a laser signal tuned on and off of an atmospheric constituent's absorption line. Significant progress has been demonstrated in developing and using both Raman and DIAL high-performance lidars for profiling atmospheric water vapor at isolated research sites and in detailed process studies, from both the ground (*Rall, 1994; Goldsmith et al., 1998; Wulfmeyer, 1998; Wulfmeyer and Bösenberg, 1998; Bösenberg, 1998; Turner et al., 2000; Wulfmeyer and Walther, 2001; Turner et al., 2002*) and the air (*Ehret et al., 1993, 1998; Browell et al., 1998; Ismail et al., 2000*). However, more routine deployment of lidars for water vapor profiling at multiple sites will require smaller, mostly autonomous, lower-cost systems that are eye-safe. The trend in recent years toward smaller and more robust lidar systems has resulted in a significant increase in the use of lidars for aerosol and cloud studies (*Spinhirne, 1993; Rall and Abshire, 1996; Shaw et al., 2001; Campbell et al., 2002; Intrieri et al., 2002*), and a similar trend is beginning to emerge for water vapor lidars. For example, previously large and complex Raman lidar systems are now being packaged in moderately sized trailers and operated routinely in long-term, largely unattended field deployments (*Rall and Abshire, 1996; Goldsmith et al., 1998; Turner et al., 2000, 2002*). However, even small Raman lidars require high-power pulsed lasers because the Raman backscattering cross section is  $\sim 4$  orders of magnitude below that of both Rayleigh and Mie backscatter (*Measures, 1984; Grant, 1991*). Raman lidar systems also require external calibration.

Differential absorption lidar (DIAL) (*Measures, 1984; Grant, 1991; Bösenberg, 1998; Kovalev and Eichinger, 2004*) systems also are moving toward smaller size and lower-cost, which may someday allow deployment in unattended networks (*Reagan et al., 1993; Rall, 1994; Reagan et al., 1996; Prasad et al., 2000; Little and Papen, 2001; Penchev et al., 2003; Machol et al., 2004*). DIAL measurements require measuring

backscattered light at wavelengths on and off an absorption line, with wavelengths sufficiently close to each other that aerosol scattering and other systematic features of the measurement cancel in a ratio. The ratio of the on- and off-line measurements can be used to determine a vertical profile of the constituent concentration. One advantage of a DIAL system compared to a Raman lidar is that the DIAL system does not require as much transmit power, making the necessary laser smaller and the eye-safe requirement easier to achieve. Another advantage is that the DIAL technique is self-calibrating when careful attention is taken to account for all sources of error in the measurement. The details of the DIAL technique will be explained further in Chapter 2. Current systems have largely used solid state lasers, dye lasers, and optical parametric oscillators, but these systems are not as small as what can be achieved with diode laser transmitters.

One promising avenue of research toward compact water vapor DIAL instruments is to use semiconductor laser transmitters (*Reagan et al.*, 1993; *Rall*, 1994; *Reagan et al.*, 1996; *Oh et al.*, 1999; *Switzer*, 1999; *Prasad et al.*, 2000; *Little and Papen*, 2001; *Penchev et al.*, 2003; *Machol et al.*, 2004). Diode lasers are compact, inexpensive, can be tuned readily, and have good spectral coverage in the near infrared spectral region where appropriate water vapor absorption lines exist. In the early 1990s, the increased availability of high-power diode lasers and photon-counting avalanche photodiode (APD) detectors led to the proposal of diode DIAL systems for boundary layer water vapor profiling (*Reagan et al.*, 1993; *Rall*, 1994; *Reagan et al.*, 1996). However, remaining challenges included low laser power and hence low signal return, spectrally broad laser pulses, and insufficiently precise or stable laser tuning.

Several variations on the theme of diode laser transmitters with APD detectors in photon-counting mode have been studied numerically (*Reagan et al.*, 1993, 1996; *Oh et al.*, 1999; *Penchev et al.*, 2003), but few systems have been implemented. *Rall*

(1994) built a DIAL system using an externally modulated AlGaAs laser near 811.6 nm and achieved mean water vapor number density measurements that agreed with measured humidity values to within 6.5% and 20% in integrated path ( $\sim 5$  km horizontal one-way path) and range-resolved (4 km horizontal one-way path) modes, respectively. *Oh et al.* (1999) reported initial experimental results from a diode-pumped Cr:LiSAF laser operating near 824.6 nm with a APD detector. They showed on- and off-line water vapor absorption profiles from the ground up to approximately 3 km, but the long time delay ( $\sim 1$  hour) between measurements prevented the retrieval of a DIAL profile. *Prasad et al.* (2000) describe a Cr:LiSAF laser for DIAL operation on a Unpiloted Airborne Vehicle (UAV), and show measurements from a breadboard system that have loose agreement with a regional radiosonde profile up to approximately 1.4 km.

*Little and Papen* (2001) reported nighttime data with multi-hour averaging times from a fiber-based lidar, showing reasonable agreement between their data, simulations, and a regional radiosonde profile up to an altitude of 2 km. Most recently, *Machol et al.* (2004) reported initial water vapor DIAL measurements from a system based on a distributed feedback (DFB) diode laser used as a seed for a diode flared amplifier, operating at 823 nm with 0.8 nm of tuning. This system provides 0.15  $\mu\text{J}$  pulse energy at pulse repetition frequencies of 6-10 kHz. Their horizontal-path measurements showed good agreement between the DIAL retrieval and surface in situ sensor water vapor data; they also showed zenith measurements that agreed well with a radiosonde profile between 800 and approximately 2500 m altitude. Machol et al. note that new laser transmitter designs are needed for better spectral coverage and larger tuning ranges, calling for “a new laser [with] a tuning range that accesses a larger selection of good water-vapor lines...”. They also note that their DFB laser is no longer available from the vendor, making it particularly important to have alternate

laser transmitter sources.

### The Montana State University Water Vapor Differential Absorption Lidar

The research performed for this dissertation involves leveraging expertise in the Montana State University (MSU) laser source development group to build a DIAL system that is cheaper, smaller, and more robust than existing field instruments and able to access a large selection of water vapor lines using a widely tunable laser transmitter. This transmitter, an External Cavity Diode Laser (ECDL), has the ability to tune across a 17 nm spectrum near 830 nm, allowing it access to multiple water vapor absorption lines of varying strengths. Because of this wide tunability, the optimal absorption line for the DIAL technique in this region can be selectively probed based upon existing atmospheric conditions. The DIAL uses an all-semiconductor transmitter and for the first time in any known DIAL instrument uses the ECDL as a seed laser source for two cascaded commercial tapered amplifiers to increase the output power. The receiver uses a fiber-coupled APD detector. Mostly commercial-off-the-shelf components are employed so that the system, including the transmitter, can be repaired quickly and relatively easily should a part fail, demonstrating a step towards the robustness needed for field deployment in multi-point arrays. The DIAL is low-power, compact, with a desktop-sized footprint, and has the ability to be made eye-safe. The goal of this project is to demonstrate that low-power DIAL instruments using widely tunable diode laser transmitters, which can be designed at multiple wavelengths, can achieve useful water vapor profiles and are acceptable candidates for use in multi-point lidar networks or satellite arrays to study water vapor flux profiles.

This dissertation describes the design, construction, characterization, and result-

ing measurements of a water vapor DIAL using a widely tunable amplified ECDL transmitter, and is summarized as follows. Chapter 2 discusses the background and theory behind lidar, and especially DIAL, measurements. An introduction to the atmosphere is given with particular emphasis on the terms, structure, and behaviors relevant to this research. The mathematical framework for the rest of the dissertation is presented. Signal-to-noise ratio calculations and model results are shown. Chapter 3 describes horizontal tuning measurements that were performed to test and validate the laser transmitter. Chapter 4 explains the analysis undertaken to select a suitable water vapor absorption line for use in the DIAL experiments, which are described in detail with results in Chapter 5. Initial water vapor profiles, taken in the Bozeman, MT, area are analyzed. Necessary improvements to the DIAL system and concluding remarks are given in Chapter 6. Appendix A describes preliminary lidar experiments and the lessons learned from them. Appendix B gives detailed information required to approve lidars for outdoor operation according to FAA rules. A user manual for operating the DIAL instrument is found in Appendix C. Finally, a list of acronyms is included as Appendix D.

## CHAPTER 2

## THEORY

Earth's Atmosphere

Earth's atmosphere is a mixture of gases and a variety of small gas and liquid particles (called aerosols) that extends over 300 miles or almost 500 km above the ground. The composition of the atmosphere is primarily nitrogen, oxygen, and argon, with trace amounts of water vapor, ozone, carbon dioxide, and other gases, as shown in figure 2.1. It comprises several distinct layers, distinguished by their heating properties. The troposphere is the layer nearest to the ground, and is where nearly all weather occurs. It is characterized by a decrease in temperature with increasing altitude of  $\sim 6.5^{\circ}\text{C}/\text{km}$  on average, called a temperature lapse rate. Simply because of gravity, most of the atmosphere by mass is located in the bottom few kilometers of the troposphere. The boundaries of the layers are very dynamic, but typically the stratosphere will begin around 10 km above the ground, and is defined by a heating of the atmosphere by absorption of ultraviolet radiation. The ozone layer is located in the stratosphere. Above the stratosphere are two other layers, the mesosphere, or middle atmosphere, and thermosphere, or upper atmosphere. The thermosphere contains the ionosphere, where Aurora occur, and is where the atmosphere merges with interplanetary gases or space (*Battan*, 1984).

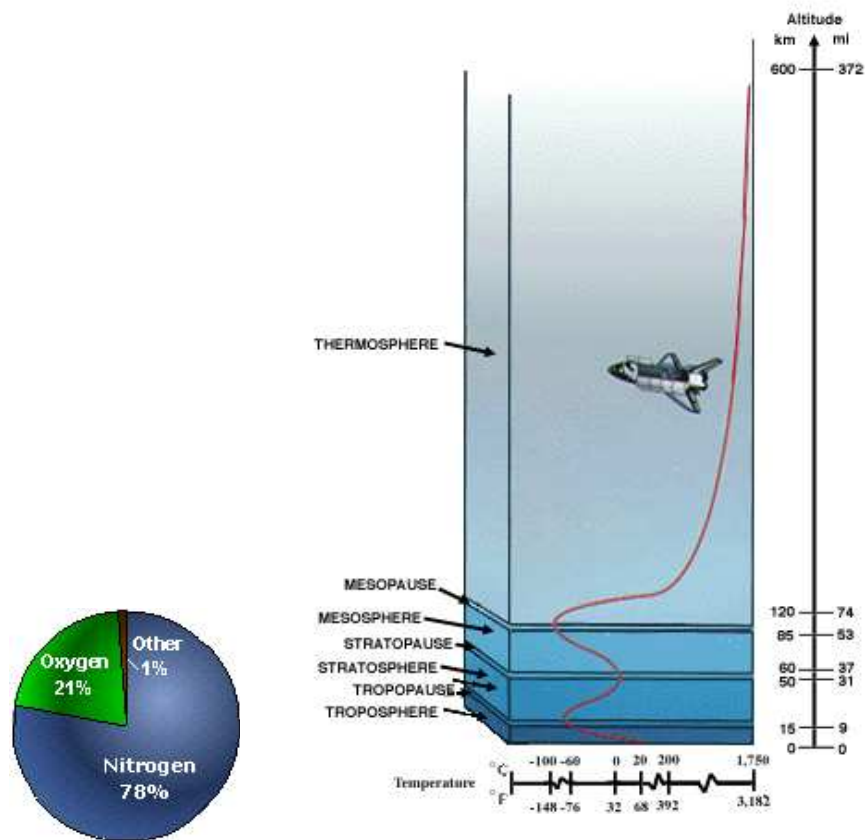


Figure 2.1: Schematics of Earth's atmospheric layers and composition. Images courtesy of NASA  
<http://liftoff.msfc.nasa.gov/academy/space/atmosphere.html>.

### Remote Sensing With Lidar

One way to probe the atmosphere is through the use of Light Detection And Ranging, or lidar. Lidar is a form of active remote sensing, where laser radiation is sent into the atmosphere to interact with it, and the results of this interaction are studied to learn more about the atmosphere. A schematic of the basic principles behind lidar is shown in figure 2.2. Laser pulses are emitted from a laser transmitter (1) with some pulse length,  $\tau$  (2). The laser interacts with atmospheric gasses and aerosols through scattering and absorption (3) characterized by a atmospheric transmission factor,  $T$ . When the laser photons scatter off of an atmospheric constituent (4), the scatter strength, probability, and direction are governed by a scattering function,  $\beta$ . Some of the scattered photons then may travel back through the atmosphere (5) again affected by a transmission factor,  $T$ . If a lidar receiver is aimed such that its field of view (FOV) contains a portion of the scattered radiation path (6) according to an overlap function,  $\xi(R)$ , its entrance aperture will collect a fraction of these photons according to the solid angle that the telescope subtends as seen from the scattering source, or  $A_r/R^2$  (7). This receiver will then have some spectral efficiency as well as a detector efficiency (8 and 9) that will cause some of the received photons to be lost,  $\xi(\lambda)$ . Finally, whatever photons do reach the detector are converted to electrons through some mechanism and are counted as a function of time elapsed from the laser pulse, which is directly related to the altitude of the scattering source in the atmosphere (10).

From this illustration, it can be seen that an equation for lidar can be built from this simple understanding, relating the counted signal photons or received power to a modification of the transmitted photons or power by the atmosphere. In fact, most derivations of the lidar equation do build the equation term-by-term through

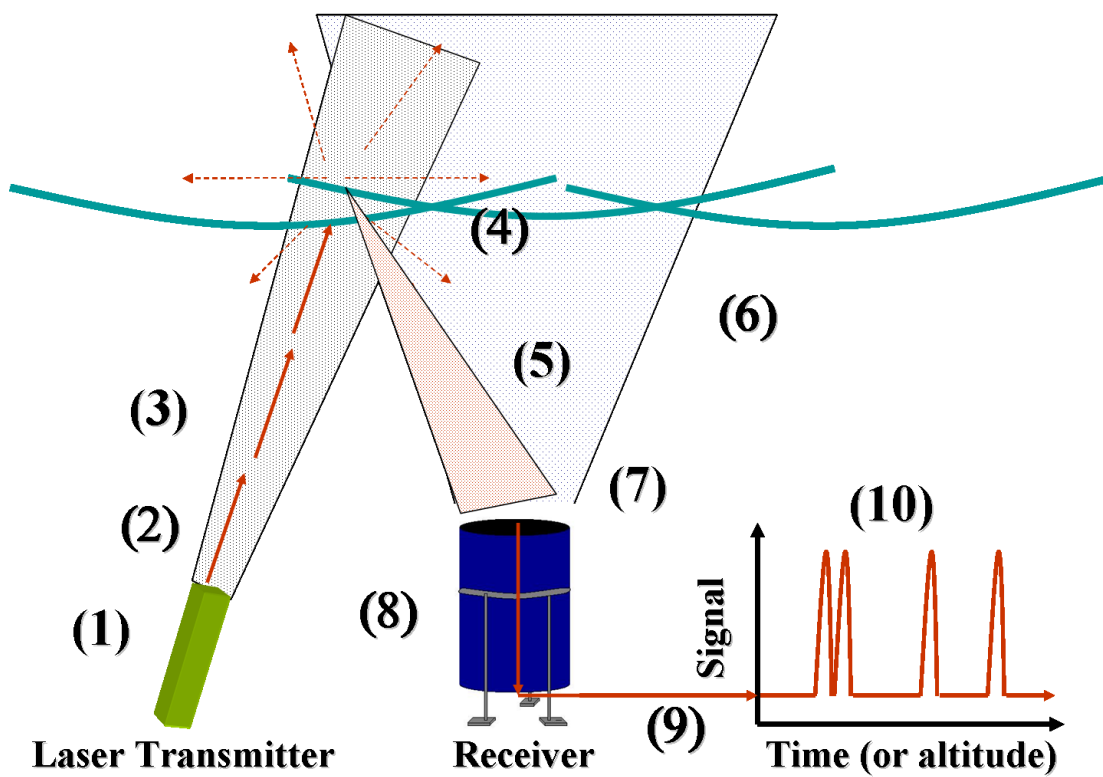


Figure 2.2: A cartoon outline of the basic principle behind lidar. See the text for a detailed explanation of each step.

these physical arguments based on a basic lidar setup and the typical response of the environment. However, the lidar equation is also derivable simply by understanding the radiometry of the situation. This derivation is rarely seen, and thus is shown here, displaying that the lidar equation is in agreement with the basics of radiometry. Through this process, the definitions of the unit volume backscatter coefficient,  $\beta$ , and the lidar geometrical compression form factor, or overlap function  $\xi(R)$ , are elucidated.

### The Lidar Equation

The lidar equation is used in a number of different laser ranging experiments to solve for or estimate various atmospheric parameters, using techniques as varied as elastic (Mie or Rayleigh) scattering, inelastic (Raman) scattering, differential absorption, and fluorescence. The lidar equation is stated most often in a form similar to (see, for instance, *Measures*, 1984, or *Kovalev and Eichinger*, 2004)

$$P_r(\lambda_L, R) = P_t \frac{A_r}{R^2} \beta \Delta z T^2 \xi(\lambda_L) \xi(R), \quad (2.1)$$

where  $P_r(\lambda_L, R) [W]$  is the power received by the photodetector at the laser wavelength,  $\lambda_L [m]$ , from range  $R [m]$ ,  $P_t [W]$  is the power transmitted by the laser,  $A_r [m^2]$  is the entrance pupil area of the receiver (typically a telescope),  $\beta [km^{-1}sr^{-1}]$  is the unit volume backscatter coefficient,  $\Delta z = c\tau/2 [m]$  is the range bin with  $c = 2.998 \times 10^8$  m/s being the speed of light and  $\tau [s]$  the laser pulse width,  $T^2 [unitless]$  is the round-trip transmission factor through the atmosphere,  $\xi(\lambda_L) [unitless]$  is the spectral transmission of the system at  $\lambda_L$ , and  $\xi(R) [unitless]$  is the lidar geometrical compression form factor, also known as the overlap function. This function is equal to 1 when the transmitted laser beam area lies completely within the field-of-view

(FOV) of the system, known as *full overlap*, and is a complicated function otherwise (see *Measures*, 1984, for example).

Since many low-power lidar applications require photon-counting detectors, the lidar equation is often written in terms of transmitted and detected photons using the conversion  $P_t = n_t(hc)/(\lambda\tau)$ , where  $n_t$  is the number of transmitted photons and  $h = 6.626 \times 10^{-34}$  J·s is Planck's constant.  $T^2$ , which will not be discussed in detail here, is given by the Beer's Law relationship

$$T^2 = \exp\left(-2 \int_0^R \alpha(r, \lambda_L) dr\right), \quad (2.2)$$

where  $\alpha [m^{-1}]$  is the atmospheric extinction coefficient including scattering and absorption (*Stephens*, 1994).  $T^2$  and  $\xi(\lambda_L)$  can be viewed in their simplest form as efficiency factors that modify the output power of the laser, and so will be folded into one term that ranges between 0 and 1, and will be taken to be constant for the purposes of this derivation.  $T^2$  is of course not a constant, and in fact contains most of the interesting physics involved with doing lidar experiments, especially in the case of Differential Absorption Lidar (DIAL). Yet, as will be shown below, it is irrelevant to the most basic radiometric derivation of the lidar equation, and would only complicate the derivation if a non-constant atmosphere were to be included. With this in mind, the lidar equation can be rewritten as

$$P_r = P_t \frac{A_r}{R^2} \beta \Delta z \xi(R) [\text{efficiency factors}]. \quad (2.3)$$

### Radiometric Derivation of the Lidar Equation

The radiometric derivation of the lidar equation will be examined in two situations: first, where the lidar system is in full overlap, and second, where the transmitted laser beam area overfills the FOV of the system or lies partially outside of it (partial overlap).

#### Full Overlap

Consider the most basic lidar setup, in which laser light from a laser transmitter is backscattered by atmospheric constituents, and a fraction of this backscattered light is collected by the receiver telescope, shown in Figure 2.3. It is assumed that the entire area being illuminated,  $A_i$ , is within the full FOV of the telescope. For a thorough treatment of the full FOV see *Stelmaszczyk et al.*, 2005. The laser is transmitting power  $P_t$  with perfect efficiency into the atmosphere. In reality,  $P_t$  would be modified by the efficiency of the transmission optics, which is contained within the system's spectral transmission factor  $\xi(\lambda)$  as defined above, and assumed to be 1 here for simplicity. The receiver will be represented simply as a focusing lens of area  $A_r$  with a detector of area  $A_d$  located at the focal point of the telescope, a distance  $f$  behind the entrance pupil. To further simplify the situation, it is assumed that the light is scattered entirely within a scattering plane at altitude  $R$ , and parallel to the receiving lens plane. Multiple scattering is not taken into consideration.

In general, the radiance  $[W/(m^2 \cdot sr)]$  at a scattering plane is given by

$$L = \frac{P}{A \cdot \Omega}, \quad (2.4)$$

where  $P$  is the power being scattered from an area  $A$  into a total scattering solid

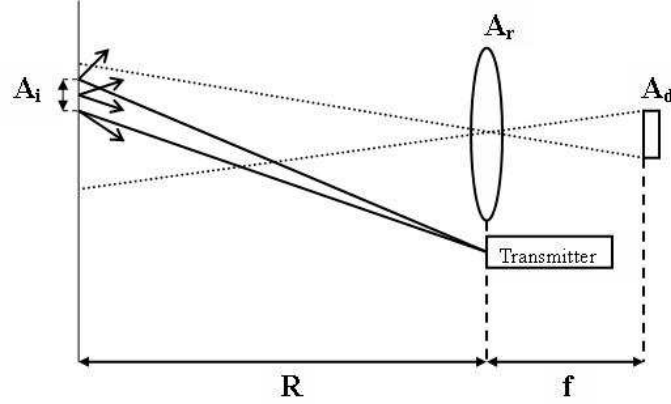


Figure 2.3: The most basic lidar configuration, consisting of a transmitting laser, a scattering target, and a receiving telescope. The transmitted beam laser is depicted with solid lines, while the telescope FOV is shown with dotted lines.

angle  $\Omega$  (Schott, 1997). For the lidar situation described, this becomes

$$L_{target} = \frac{P_t}{A_i \cdot \Omega_{target}}, \quad (2.5)$$

where  $A_i$  is the illuminated area, and  $\Omega_{target}$  is  $\pi$  if the scattering plane is Lambertian, or could be a complicated function of wavelength and angle, as is common in the atmosphere. It is assumed for the moment that  $A_i$  is perfectly scattering in two ways. First, the entire area, not just a fraction of  $A_i$ , is scattering the incoming light, so that

$$\frac{A_{scatter}}{A_i} = 1, \quad (2.6)$$

where  $A_{scatter}$  is the area actually causing scattering. Second, all of the incoming light is scattered, so that  $A_i$  has a perfect reflectivity  $\rho = 1$ . In actual lidar measurements, these two efficiencies must be taken into account, as will be seen in the lidar-comparison section below.

The power at the receiver is given by multiplying the target radiance,  $L_{target}$ , by

the receiver throughput, or  $A \cdot \Omega$  product,

$$P_r = L_{target} A \Omega. \quad (2.7)$$

The throughput consists of an area and a projected solid angle *as viewed from that area*. In this case, there are two equivalent ways to describe the throughput. If the area selected is the receiver area,  $A_r$ , then the solid angle that must be used is the solid angle subtended by the scattering area as seen from the receiver,  $A_i/R^2$ . Conversely, if the area selected is the area of the scattering source,  $A_i$ , then the solid angle that must be used is the solid angle subtended by the receiver area as seen from the source,  $A_r/R^2$ . It is assumed that  $A \ll R$  in both cases so that the small-angle approximation of the projected solid angle may be used. Both methods of defining the throughput are identical and can now be used in equation (2.7) to write the power at the receiver,

$$P_r = L_{target} A_i \frac{A_r}{R^2}. \quad (2.8)$$

Substituting for  $L_{target}$  with equation (2.5), the received power at the telescope in the case of full overlap is

$$P_r = P_t \frac{A_r}{R^2} \frac{1}{\Omega_{target}}. \quad (2.9)$$

### Partial Overlap

Now consider the situation for which the divergence and/or pointing angle of the transmitting laser causes the illuminated area to be only partially contained within the FOV of the system, known as partial overlap. The same assumptions are made for the scattering target. The situation is depicted in Figure 2.4.

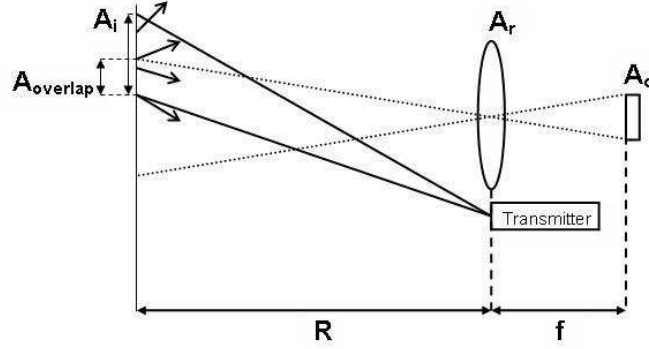


Figure 2.4: Partial overlap of the transmitted beam area (solid lines) with the receiver's FOV (dotted lines).

The radiance at the scattering plane for this situation is given again by equation (2.5). The power at the receiver, however, will now be written as

$$P_r = L_{target} A_r \frac{A_{overlap}}{R^2}. \quad (2.10)$$

Notice that  $A_i$  has in this case been replaced by  $A_{overlap}$ , the area of overlap between the area “seen” by the receiver and  $A_i$ . This can be understood in the above equation as the receiver pupil only receiving light from the solid angle subtended by the area illuminated within its FOV,  $A_{overlap}/R^2$ . Equivalently, by reversing the areas, it indicates that only the light scattering from area  $A_{overlap}$  will be collected by the solid angle subtended by the receiver  $A_r/R^2$  as seen from the scattering plane. Combining equations (2.5) and (2.10) gives the power at the receiver while in partial overlap,

$$P_r = P_t \frac{A_r}{R^2} \frac{1}{\Omega_{target}} \left( \frac{A_{overlap}}{A_i} \right). \quad (2.11)$$

The power received at the receiver in the case of partial overlap differs from the full overlap case (equation (2.9)) only by the term in parentheses. This term is the

overlap factor,

$$\frac{A_{overlap}}{A_i} = \xi(R), \quad (2.12)$$

as discussed above (*Stelmasczyk et al.*, 2005). When  $A_{overlap}$  contains the entire illuminated area,  $A_i$ , the system is in full overlap and  $\xi(R) = 1$ .

### Comparison With the Lidar Equation

Equation (2.11) is similar to equation (2.3), the lidar equation. In fact, it is identical if it can be shown that the term  $\beta\Delta z$  is equal to  $\Omega_{target}^{-1}$ .  $\beta$  generally is defined as

$$\beta = \sigma \cdot N \quad (2.13)$$

where  $\sigma [m^2 sr^{-1}]$  is the differential scattering cross section of the target and  $N [m^{-3}]$  is the number of particles per unit volume involved with the scattering. In lidar setups where the transmitter is close to the receiver compared to  $R$ ,  $\sigma$  is taken to be the backscattering cross section,  $\sigma_\pi$ . It is assumed that the range bin  $\Delta z$  is small compared to  $R$ , such that  $\sigma_\pi$  is constant across the entire range bin. In simplest terms,  $\sigma_\pi$  depends on the effective scattering area and backscattering solid angle of the particle,

$$\sigma_\pi = \frac{A_{eff,particle}}{\Omega_{particle}}. \quad (2.14)$$

The particles involved with the scattering process,  $n$ , are only those that are illuminated by the laser, contained within a volume,  $V_i$ , defined by the laser pulse,

$$N = \frac{n}{V_i}, \quad (2.15)$$

where

$$V_i = A_i \cdot \Delta z. \quad (2.16)$$

Combining  $\sigma$  and  $N$  in equation (2.13) using equations (2.14), (2.15), and (2.16) gives the unit volume backscatter coefficient of the illuminated volume,

$$\beta = \frac{A_{eff,particle} \cdot n}{\Omega_{particle} \cdot A_i \cdot \Delta z}, \quad (2.17)$$

and,

$$\beta \Delta z = \frac{A_{eff,particle} \cdot n}{\Omega_{particle} \cdot A_i}. \quad (2.18)$$

Notice that for an atmosphere constant in composition over the time scale of a laser pulse,  $n \propto A_i$  such that as  $A_i$  increases,  $n$  increases proportionally, making  $n/A_i$  constant.  $A_{eff,particle}$  and  $\Omega_{particle}$  are simply properties of the atmospheric constituent causing the scattering, and  $\beta \Delta z$  is therefore constant for a given wavelength, lidar setup, and set of atmospheric conditions. Ignoring particle shadowing effects,  $A_{eff,particle} \cdot n$  is the total area of the scattering particles in the volume  $A_i \cdot \Delta z$ , or simply the area from which the incoming light is being scattered,  $A_{scatter}$ , as defined in section 2.  $\Omega_{particle}$  is the single-particle solid angle response averaged over many particles, and therefore the solid angle of a group of particles will average to this same quantity when the receiver is close to the transmitter, so that  $\Omega_{particle} = \Omega_{target}$ , assuming that  $\sigma$  is equal to  $\sigma_\pi$  for each particle in the volume. Taking these points together, or more rigorously, integrating the differential scattering cross section  $\sigma$  over the illuminated volume, gives

$$\beta \Delta z = \frac{1}{\Omega_{target}} \frac{A_{scatter}}{A_i}, \quad (2.19)$$

where  $\Omega_{target}$  is the same quantity first introduced in equation (2.5). If the scattering medium is completely opaque and perfectly reflecting, as was assumed for the targets in the Full Overlap and Partial Overlap sections above, then equation (2.6) holds true and equation (2.19) reduces to

$$\beta\Delta z = \frac{1}{\Omega_{target}}, \quad (2.20)$$

as desired. In realistic lidar measurements the atmosphere is neither completely opaque nor perfectly reflecting, such that  $A_{scatter} < A_i$  and  $\rho < 1$ . These actual scattering efficiencies then have to be considered and will reduce the power backscattered to the receiver.

Returning to the simple lidar situation, equation (2.11), the power at the receiver for a lidar system in partial overlap, can now be rewritten with the results found in equations (2.12) and (2.20):

$$P_r = P_t \frac{A_r}{R^2} \beta\Delta z \xi(R). \quad (2.21)$$

Including the efficiency factors that modify the transmitted power in a real lidar system gives equation (2.3), the lidar equation:

$$P_r = P_t \frac{A_r}{R^2} \beta\Delta z \xi(R) [efficiency\ factors]. \quad (2.22)$$

Therefore, the radiometric derivation for the power received in a partially or fully overlapped lidar system is equivalent to the lidar equation itself, showing that the lidar equation can be derived through simple radiometric arguments. All terms in the lidar equation originate from terms defined by a simple radiometric understanding of the basic lidar setup. This derivation elucidates that the overlap function, or lidar

geometrical compression form factor  $\xi(R)$ , is fundamentally a ratio of the area of the transmitted beam that overlaps with the receiver FOV. It is also shown that the unit volume backscatter coefficient multiplied by the range bin in the lidar equation,  $\beta\Delta z$ , is equivalent to the inverse of the radiometric target backscatter solid angle,  $\Omega_{target}^{-1}$ . Both cases of full overlap and partial overlap of the transmitted laser beam and the receiver FOV are consistent with their radiometric counterparts.

### DIAL Equation Derivation

It is clear from inspection of the lidar equation, equation 2.1, that many terms can be directly measured in the laboratory. However, there are some terms that cannot be easily measured or estimated, such as the unit volume backscatter coefficient,  $\beta$ , or the atmospheric extinction coefficient,  $\alpha$ , inside the atmospheric transmission factor,  $T$ , which can be expanded as

$$\alpha(r, \lambda_L) = \kappa(r, \lambda_L) + \sigma(r, \lambda_L)N(r), \quad (2.23)$$

where  $\kappa(r, \lambda_L) [km^{-1}]$  is the atmospheric extinction factor due to all extinction excluding absorption and  $\sigma(r, \lambda_L)N(r) [km^{-1}]$  is the atmospheric extinction due to absorption, where  $\sigma(r, \lambda_L) [m^2]$  is now the absorption cross section of an atmospheric constituent and  $N(r) [m^{-3}]$  is the number density of absorbing molecules. One difficulty with all lidar measurements is that there are more unknowns in the lidar equation, meaning estimations have to be made of the value of some terms in order to determine others, leading to uncertainties. One technique that is used to circumvent some of these uncertainties is called Differential Absorption Lidar (DIAL).

The theory behind DIAL is to form the difference in the logarithm of  $P_r(\lambda_L, R)$

evaluated at ranges of  $R$  and  $R + \Delta R$  at two wavelengths:  $\lambda_{on}$  located on the line center of an absorption line of some atmospheric constituent such as ozone or water vapor, and  $\lambda_{off}$  located some spectral distance away from the absorption line center, in another part of the absorption continuum for the case of ozone or completely clear of the absorption line in the case of water vapor (*Schotland, 1974*). From equation 2.1 then,

$$\begin{aligned}
 \ln P_{on,off}(R) - \ln P_{on,off}(R + \Delta R) = & \ln \left\{ P_{t,on,off} \frac{A_r}{R^2} \beta_{on,off}(R) \Delta z \right. \\
 & \cdot \exp \left( -2 \int_0^R \alpha(r, \lambda_L) dr \right) \cdot \xi(\lambda_L)_{on,off} \xi(R) \left. \vphantom{\frac{A_r}{R^2}} \right\} \\
 & - \ln \left\{ P_{t,on,off} \frac{A_r}{(R + \Delta R)^2} \beta_{on,off}(R + \Delta R) \Delta z \right. \\
 & \cdot \exp \left( -2 \int_0^{R+\Delta R} \alpha(r, \lambda_L) dr \right) \\
 & \cdot \xi(\lambda_L)_{on,off} \xi(R + \Delta R) \left. \vphantom{\frac{A_r}{(R + \Delta R)^2}} \right\} \tag{2.24}
 \end{aligned}$$

Since  $P_{t,on,off}$ ,  $A_r$ ,  $\xi(\lambda_L)$ , and  $\Delta z$  are the same at  $R$  and  $R + \Delta R$ , they will cancel out of the equation. Evaluating the integrals, combining the range terms, and simplifying leaves

$$\begin{aligned}
 \ln P_{on,off}(R) - \ln P_{on,off}(R + \Delta R) = & \ln \beta_{on,off}(R) - \ln \beta_{on,off}(R + \Delta R) \\
 & + \ln \left( 1 + \frac{2\Delta R}{R} + \left( \frac{\Delta R}{R} \right)^2 \right) \\
 & + \ln \xi(R) - \ln \xi(R + \Delta R) \\
 & + 2\kappa_{on,off}(\Delta R) \cdot \Delta R \\
 & + 2\sigma_{on,off}(\Delta R) \cdot N(\Delta R) \cdot \Delta R. \tag{2.25}
 \end{aligned}$$

Now, if the off-line terms are subtracted from the on-line terms,

$$\begin{aligned}
& (\ln P_{on}(R) - \ln P_{on}(R + \Delta R)) - (\ln P_{off}(R) - \ln P_{off}(R + \Delta R)) \\
&= \ln \frac{\beta_{on}(R)}{\beta_{on}(R + \Delta R)} - \ln \frac{\beta_{off}(R)}{\beta_{off}(R + \Delta R)} \\
&\quad + 2(\kappa_{on}(\Delta R) - \kappa_{off}(\Delta R)) \cdot \Delta R \\
&\quad + 2(\sigma_{on}(\Delta R) \cdot N(\Delta R) - \sigma_{off}(\Delta R) \cdot N(\Delta R)) \\
&\quad \cdot \Delta R.
\end{aligned} \tag{2.26}$$

Notice that the overlap factor is completely removed from the equation. If the assumption is made that the on-line and off-line wavelengths are so spectrally close that the unit volume backscatter coefficient,  $\beta$ , and atmospheric extinction factor,  $\kappa$ , are unchanged at the two wavelengths, the equation simplifies and  $N(R + \Delta R)$  can be solved for, forming the DIAL equation,

$$N(R + \Delta R) = \frac{1}{2(\sigma_{on} - \sigma_{off})\Delta R} \ln \left[ \frac{P(R)_{r,on}P(R + \Delta R)_{r,off}}{P(R + \Delta R)_{r,on}P(R)_{r,off}} \right]. \tag{2.27}$$

Using the DIAL equation allows a measurement of the number density as a function of range to be solved for, without having to know many other atmospheric parameters.  $\sigma_{on,off}$  can be calculated using HiTRAN 2000, a radiative transfer database (*Rothman et al.*, 2003), and inputs from a colocated radiosonde for increased accuracy. The other quantities are known.

## CHAPTER 3

## HORIZONTAL TUNING EXPERIMENTS

Introduction

Prior to attempting vertically pointing water vapor DIAL experiments, horizontally pointing lidar experiments were completed to test and verify various components similar to those that were used in the vertical water vapor DIAL system, including in particular, the actual tuning of the laser. The first step towards constructing a water vapor DIAL with a widely tunable diode laser transmitter is to verify that the transmitter has the ability to tune on and off of water vapor absorption lines while operating in a lidar configuration. To accomplish this task, the laser beam must be tuned to a water vapor absorption line and transmitted across a pathlength containing water vapor, and a measurement must be made of how much laser power is absorbed by the water vapor. The laser must then be tuned completely off of the absorption line, and the power measurement should verify that the absorption due to water vapor is no longer present.

Several experiments at different locations were attempted without success before the horizontal lidar was moved to the roofport room of Cobleigh Hall on the MSU campus. There, continuous wave (cw) measurements were made as an initial test of the system before pulsed measurements were attempted. The horizontal lidar transmitter used the same External Cavity Diode Laser (ECDL) and injection-seeded tapered amplifier, operating near 830 nm, that was used in the vertical water vapor DIAL system. It was aimed at hard targets, increasing the return signal by orders of

magnitude over a vertically-pointing lidar that only receives backscattered photons from the atmosphere, allowing the tuning to be tested without needing to optimize a weak return signal. The steps taken to arrive at these measurements are described in this chapter. These early measurements, as well as a full description of the ECDL and lidar setups, are described in the literature (*Obland et al.*, 2005, 2006a,b).

### Steam Tunnel Experiments

An estimate of the pathlength needed to measure absorption by water vapor was needed before any absorption experiments could be designed. Modifying equation 2.2 for a one-way, homogeneous pathlength gives  $T = e^{-\alpha R}$ . Using this equation and assuming that the absorption extinction coefficient is completely due to water vapor absorption such that there is no scattering allows for a simple estimation to be made of the range needed to measure water vapor absorption. Table 3.1 shows the estimated pathlengths needed for three candidate water vapor absorption lines within the tuning range of ECDL's that have been built at MSU, ordered left to right from strongest to weakest. The absorption coefficients were taken from HiTRAN 2000, a radiative transfer database (*Rothman et al.*, 2003), calculations using a US Standard Atmosphere, which tends to be more moist than the atmosphere around Bozeman, meaning that these absorption results are probably overestimates.

| Wavelength (nm)            | 834.459 | 831.615 | 850.818 |
|----------------------------|---------|---------|---------|
| Distance to 10% Absorption | 387 m   | 450 m   | 2564 m  |
| Absorption at 440 m        | 11.30%  | 8.90%   | 1.80%   |
| Absorption at 880 m        | 21.30%  | 16.90%  | 3.60%   |

Table 3.1: Estimated pathlengths needed to obtain measurable absorptions due to water vapor in the atmosphere for three candidate water vapor absorption lines within tuning range of MSU ECDL's, ordered left to right from strongest to weakest.

It is immediately apparent that in the 830 nm region of the spectrum, even a relatively strong line such as the one at 834.459 nm is still too weak to give a measurable absorption in transmitted power over a range of less than several hundred meters. This fact makes a lab measurement of absorption very difficult to accomplish without access to a gas absorption cell with a very long pathlength. A longer pathlength, preferably within a controlled space, was required.

The first idea conceived for accomplishing the long-pathlength absorption experiments was to perform the experiments in the steam tunnels running underneath the Montana State University campus. Access to the steam tunnels is tightly controlled, greatly minimizing the chance of someone being injured by stepping into the laser beam. Tours of the tunnels showed that the water vapor content of the air nearly matched the ambient level of the outside air. The longest one-way pathlength was about 220 meters, but could be increased to 440 meters or 880 meters by using mirrors to reflect the beam back to the detector. Performing experiments in the steam tunnels was a difficult endeavor due to the lack of elevator access, meaning all equipment had to be carried by hand down several flights of stairs. Also, compatible power outlets were hard to find, limiting the experiment location to one spot within the tunnels.

Several data runs were performed in the steam tunnels with a ECDL centered around a wavelength of 850.818 nm. The laser and associated instruments were set up on heavy carts and optical tables. The ECDL output was expanded, collimated, and sent down the length of the tunnel. Two, 2-inch mirrors were mounted on a portable optical table at the other end of the tunnel to make the first and third reflections. After the third reflection, the laser returned to the starting point of the tunnel, where the beam was focused onto a detector. A reference power measurement of the original transmitted beam was made as well, to remove fluctuations in the laser power from the final results. A picture of the experiment is shown in figure 3.1.



Figure 3.1: A picture of the steam tunnel experiment.

None of the data runs in the steam tunnels succeeded in measuring absorption in the laser beam. Tests with a Helium-Neon laser, visible at 633 nm, showed that mechanical vibrations within the tunnels were significant, making it difficult to keep the laser beam aligned on three mirrors and a detector simultaneously. Even after placing all mirrors on sand bags to dampen these mechanical vibrations, thermal variations along the length of the tunnels (measured to be  $\pm 10^\circ$  at times) still caused unacceptable beam distortion and misalignment due to air turbulence. Even if alignment was not an issue, trying to find absorption on the level of a few percent would still be difficult or impossible to measure due to the power variations in the laser. A different laser with access to stronger water vapor absorption lines would be required, as well as a new experiment location with less vibration and thermal variation.

A suggested possible solution to these problems was to perform horizontal absorption measurements on the roof of Cobleigh Hall on the MSU campus, using other buildings around campus or in the city of Bozeman as hard reflection targets. How-

ever, because the weather could not be controlled and an adequate, accurate pointing mechanism for the laser would be difficult to design, the decision was made to perform horizontal, hard target absorption measurements through the window in the roofport room, on the sixth floor of Cobleigh Hall. The environment and beam-pointing could be well controlled within this room. These horizontal absorption experiments from the roofport room are described in the rest of this chapter.

### Roofport Experiments

The ECDL used in the steam tunnel experiments was replaced with a tunable ECDL transmitter with a center wavelength near 830 nm, which was operated with a lidar receiver to measure atmospheric transmission across water vapor absorption lines centered at 829.022 nm and 831.615 nm. To focus on the tuning ability of this transmitter, backscatter from three distant hard targets was measured with the laser operating initially in cw mode. Following the cw measurements, the transmitter was operated in a pulsed mode, but with pulses of longer temporal duration than would be employed in the actual atmospheric DIAL system. While the pulse length prohibited range resolution, the experiment was performed as an initial demonstration that the transmitter can maintain its performance characteristics when pulsed. Finally, pulses with widths of 500 ns (range resolution of 75 m) were used to demonstrate that the system could perform the necessary tuning under realistic DIAL conditions.

### System Description

The experimental setup is shown in figure 3.2. The horizontal tuning experiments were built around several key components, which are described in more detail individually below.

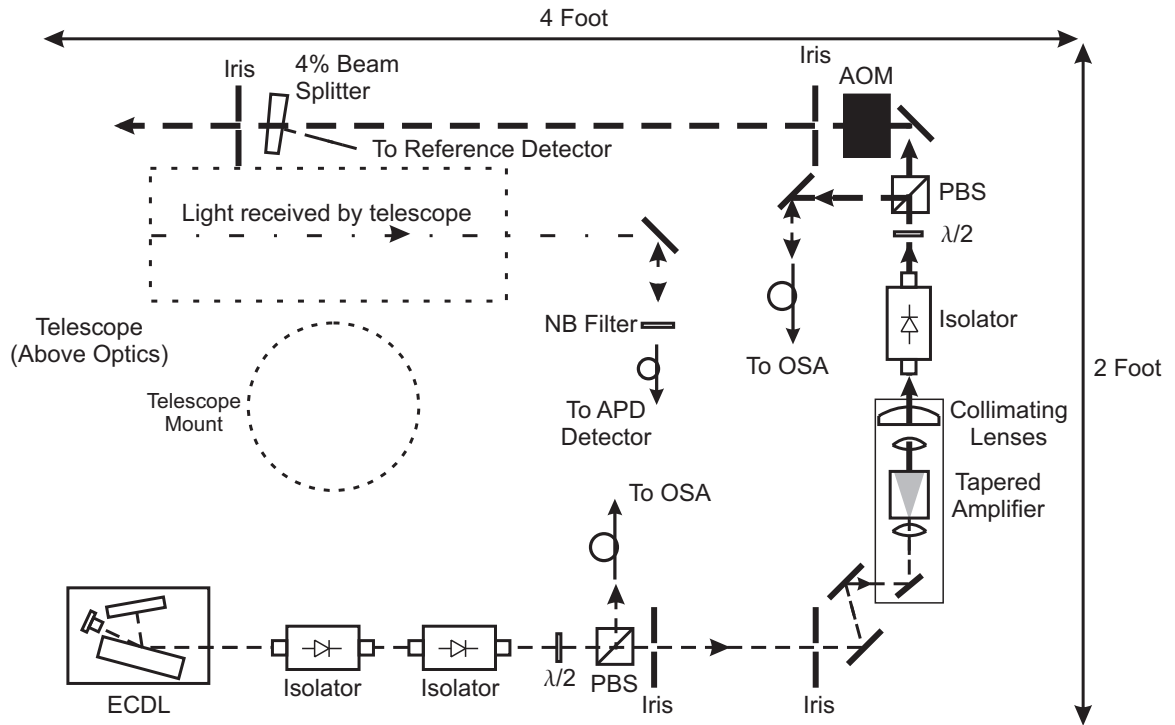


Figure 3.2: A schematic diagram of the horizontal tuning experiment. A tunable ECDL is coupled into a tapered flared amplifier. The amplified output is sent out into the atmosphere and a 28-cm telescope is used to collect the backscattered light. The light collected by the telescope is measured using an avalanche photodiode operating in the Geiger mode.

The output of the ECDL passes through two Faraday isolators to prevent optical feedback from affecting the performance of the ECDL or damaging the diode laser. After the isolators, the light is incident on a half-wave plate and polarizing beam splitter (PBS). One polarization output of the PBS is launched into an optical fiber for monitoring the ECDL wavelength on a wavemeter with a resolution of 10 MHz, while the second polarization output of the PBS was free-space coupled into the tapered amplifier by using two irises for alignment. By rotating the half wave plate, the amount of light sent to the amplifier and fiber can be adjusted. The output of the amplifier was collimated and sent through a Faraday isolator preventing damage to the tapered amplifier from optical feedback. Light was next incident on a second half-wave plate and PBS. One polarization output of the second PBS was launched into an optical fiber for monitoring the output of the tapered amplifier on an optical spectrum analyzer (OSA) with a resolution of 0.1 nm. For the cw and initial pulsed experiments, the second polarization output of this PBS was transmitted off of the optical table after being directed through two widely-spaced irises for precision alignment with the chosen target. For the faster pulsing experiments, the second polarization output of the PBS was first sent through an acousto-optic modulator (AOM) that pulsed the cw beam, as described below, and then transmitted off of the optical table through the two irises. In all experiments, the transmit beam was passed through a  $\sim 4\%$ -reflective beam splitter before leaving the table. The reflected signal was sent to a reference detector to monitor changes in the transmit power as the transmitter tuned. These fluctuations were normalized out of the final data. The remaining 96% of the light was transmitted into the atmosphere. Alignment was achieved by visually aiming the instrument such that the target area defined by the irises was in full view of the telescope. Care was taken to avoid any visible steam vents or exhaust plumes along the horizontal path length. The final transmit power from this system was typically

between 80 mW and 120 mW, although this was again reduced by several percent because of reflection off of the room window.

Light scattered from the atmosphere and the distant hard target was collected by an optical receiver that employed a Schmidt-Cassegrain telescope, sent through a 10-nm-wide interference filter centered at about 830 nm and a 650- $\mu$ m core-diameter optical fiber, to a photon-counting avalanche photodiode (APD) detector module operating in photon-counting mode. The telescope field of view is about 13.5 mrad, while the transmitted beam divergence was 1.43 mrad, ensuring that the beam spot at the target was always completely within full overlap with the receiver. A multi-channel scalar (MCS) was used to count the APD pulses and bin them in time.

Laser tuning and data acquisition were operated via computer control and LabVIEW software. The control program simultaneously measured both the wavelength of transmitted laser light and the reference beam power, initialized the MCS and other instruments used to operate the experiment, and began data collection. Since distance resolving did not need to be considered for the cw and preliminary pulse measurements, the mean count in all of the bins was calculated. For the faster pulsing experiments, counts in each bin were averaged for some amount of time, and data analysis used the counts from the bin or bins containing signal reflected from the target. The reference power, mean count, and laser frequency at one wavelength were recorded to a data file after which the computer tuned the laser by adjusting the voltage applied to the piezo-electric tuner. The MCS counter was cleared and the data acquisition process reinitiated until a scan across an absorption feature was completed. The temperature of the ECDL was adjusted manually when necessary to shift the mode-hop-free region across the absorption, allowing for a scan of greater than 50 GHz.

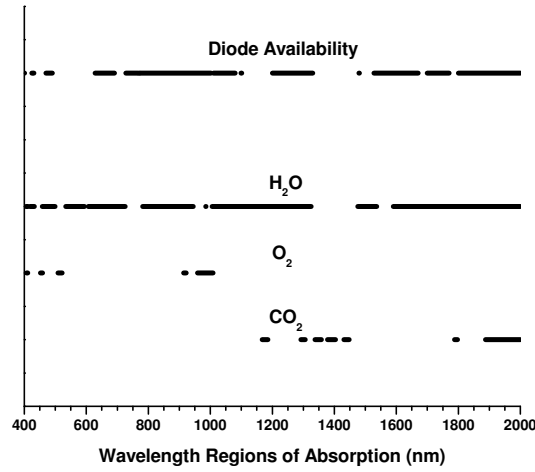


Figure 3.3: A plot showing absorption features of atmospheric constituents of current scientific interest in the visible and near-infrared optical spectrum, compared to the availability of diodes with wavelengths in this region.

External Cavity Diode Laser (ECDL) The key to the entire water vapor DIAL described herein is the ECDL built at MSU. External cavity diode lasers (ECDL's) have found applications in a variety of areas, including molecular spectroscopy (*Nguyen et al.*, 1994; *Aumiller et al.*, 2004) and as seed sources for differential absorption lidar systems (*Machol et al.*, 2004; *Repasky et al.*, 2004; *Obland et al.*, 2006a). Diode lasers offer wide spectral coverage and tunability, especially in wavelength regions containing absorption features of scientifically interesting atmospheric constituents, as shown in figure 3.3. ECDL configurations can narrow the spectral bandwidth and raise the spectral purity of the diode output. The laser source development group at Montana State University has extensive experience building high-quality ECDL's, which was leveraged to develop the highly tunable transmitter for the water vapor DIAL. A detailed description of how the ECDL was designed and built can be found in *Switzer*, 1999.

Several different type of external cavity configurations exist for diode lasers, but

placing the diode in a Littman-Metcalf external cavity configuration (*Littman and Metcalf*, 1978) such that the output of the diode laser is incident on a diffraction grating allows for a stable tuning method to be employed. Another advantage of this configuration is that the output of the ECDL remains pointed in the same direction, unlike other configurations. A schematic of a ECDL in a Littman-Metcalf configuration built at Montana State University is shown in figure 3.4. The output of a diode laser is collimated and strikes a diffraction grating at a grazing incidence angle, spatially separating the wavelengths of the diode's broad spectral output. The zeroth-order reflection is used as the output for the ECDL. A retro-reflecting roof prism is tilted at the correct angle to direct one spectral component of the first-order reflection back to the diode laser via a second reflection from the diffraction grating, forcing the laser to run single-mode at the chosen wavelength. The spectral characteristics of the ECDL are defined by the frequency of the light fed back into the diode laser and the resonant condition that requires an integer number of half wavelengths to fit within the external cavity. Tuning the ECDL is accomplished by rotating the roof prism around a pivot point (*McNicholl and Metcalf*, 1985; *de Labachellerie and Passedat*, 1993) to change the frequency of light fed back to the diode laser while simultaneously changing the external cavity length, so that a constant integer number of half wavelengths is maintained within the external cavity (*Meng et al.*, 2000; *Repasky et al.*, 2001). If the optical cavity length changes as the roof prism is rotated so that the same number of half wavelengths is maintained within the optical cavity as the wavelength changes, continuous tuning will result. If this is not the case, a mode hop will occur.

A picture of an ECDL that was built at Montana State University is shown in figure 3.5. A 150-mW diode laser with a center wavelength of 830 nm (SDL-5421) is collimated using an aspheric lens with a focal length of 4.5 mm and a numerical

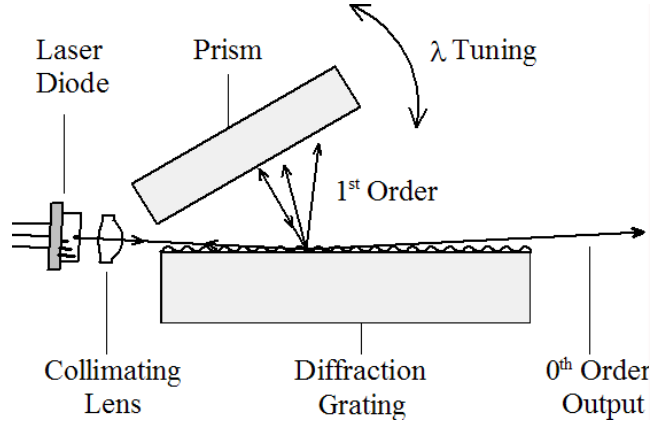


Figure 3.4: A schematic of a tunable external cavity diode laser in a Littman-Metcalf configuration. The collimated light from a laser diode is incident on the diffraction grating. The zeroth order reflection is used as the output from the external cavity laser while the first order reflection is used to spatially separate the spectral output from the diode. The prism serves as a retroreflector to provide optical feedback to the diode laser via a second reflection from the diffraction grating and is used to control the operating frequency of the external cavity laser. Tuning is achieved by rotating the prism.

aperture of 0.55 (Thor Labs 350230-B). The collimated light is next incident on a 1600 line/mm grating, 15 mm wide by 60 mm long by 10 mm thick (Spectrogon), at a grazing angle of 3 degrees. The first-order reflection from the diffraction grating is found from  $\cos\theta_{out} = \cos\theta_{in} - \lambda/d$  to be  $109^\circ$ , where  $\theta_{in}$  ( $\theta_{out}$ ) is the angle between the incoming (outgoing) beam and the plane of the diffraction grating,  $\lambda$  is the wavelength, and  $d$  is the line spacing of the diffraction grating. The first-order reflection is incident on a roof prism that directs the light back into the diode laser via a second reflection from the diffraction grating, providing optical feedback to the diode laser. The advantage of using the prism over a mirror is that it is easier to align since it acts like a corner cube in the non-dispersive direction. The 3.8-cm-long external cavity has a free spectral range of 3.9 GHz.

The roof prism rotates so that the cavity length changes in concert with the wavelength of light fed back to the diode laser, allowing for mode-hop-free tuning

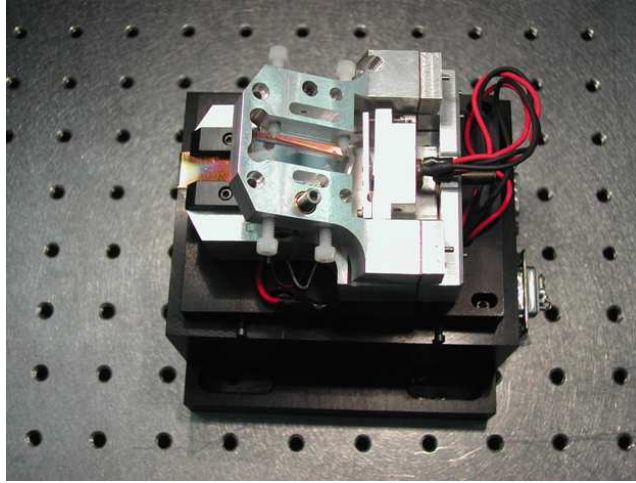


Figure 3.5: A picture of an ECDL built at Montana State University. This laser can be tuned from 824 nm to 841 nm.

(*McNicholl and Metcalf*, 1985; *de Labachellerie and Passedat*, 1993). The roof prism can be rotated mechanically by a 3/16-100 screw for coarse tuning. Fine rotation of the roof prism is achieved by applying a voltage to a piezo-electric stack (Thor Labs AE0505D16), giving mode-hop-free tuning of over 20 GHz at a fixed temperature. The roof prism can be rotated by a piezoelectric tuner (PZT) allowing the output of the ECDL to be tuned electronically (*Littman and Metcalf*, 1978).

The ECDL is placed on a thermo-electric cooler (TEC) for temperature stabilization, and monitored and controlled by a commercial temperature and current controller (ILX LDD3722) to within 0.1 degrees Celsius. The same controller is used to supply a drive current to the diode laser, which is operated in a cw mode. The output of the ECDL is sent through a Faraday isolator to prevent unwanted feedback from affecting its performance.

The ECDL performance is summarized as follows. The coarse tuning varies from 824 nm to 841 nm by mechanically changing the angle of the retroreflective prism. By adjusting the piezo-electric stack, we can also obtain a mode-hop-free tuning range greater than 20 GHz. The beginning and ending wavelengths of this tuning range

can be altered by adjusting the diode temperature, typically between 19.2 and 20.2 degrees Celsius. The diode current is locked at about 37 mA. The full-width at half-maximum line-width is less than 200 kHz, as determined by beating experiments (*Repasky et al.*, 2002). The maximum output power is 20 mW, with a side-mode suppression of greater than 45 dB, as measured on an OSA. ECDLs have been built at Montana State University with similar performance at center wavelengths of 790, 808, 830, 850, 935, 1050, 1160, 1330, and 1540 nm. Other wavelengths such as 950 nm, where water vapor has strong absorption features, can be reached easily through simple modifications of the ECDL design. Commercial tunable ECDLs are also available (*New Focus Product Guide*, 2007). The advantage of building them at Montana State University is that wavelengths specific to DIAL applications can be easily achieved.

Tapered Amplifier In spite of its narrow linewidth and broad tunability, the ECDL has low output power that is limited to  $< 20$  mW to extend the diode's lifetime and improve the tuning characteristics. The ECDL is therefore used to injection seed a semiconductor tapered amplifier (Sacher Lasertechnik TA830, figure 3.6) to obtain higher optical power, up to 500 mW, while maintaining the spectral properties of the seed laser. This power was never achieved in practice, however, as the seed power from the ECDL was only about 5 mW after traveling through two Faraday isolators, and therefore was unable to saturate the TA. Even with low seed power, the spectral characteristics of the ECDL, including linewidth and tunability, are transferred to the output of the tapered amplifier (*Repasky et al.*, 2001). Note that when the amplifier is not powered, about  $2 \mu W$  of power is still transmitted from the ECDL through the amplifier. Therefore, the ratio of the output of the amplifier when it is on to the transmitted power of the seed laser with the amplifier off is about 50 dB. The

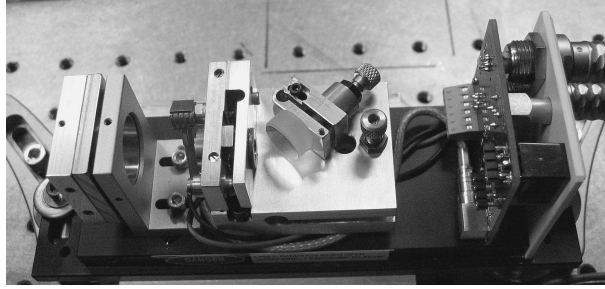


Figure 3.6: A picture of the Sacher Lasertechnik TA830 tapered amplifier. The input mirror used for seeding the TA is visible in the center of the picture. The collimating optics are on the far left.

amplifier's temperature and current are controlled and monitored by a commercial laser diode controller (Sacher Lasertechnik Pilot P3000, figure 3.7). The amplifier temperature and current are set at about 21 degrees Celsius and 2.5 A. Figure 3.8 shows an OSA trace of the optical power at the amplifier output, plotted as a function of wavelength and attenuated to avoid damaging the OSA. A tuning range of 17 nm, from 824 to 841 nm, is obtained when the ECDL is tuned. The side-mode suppression ratio of the amplifier output reaches greater than 45 dB, which is identical to the ECDL output. For spatial quality,  $M^2$  values of the amplifier output beam have the typical values between 1.4 and 2.5, as claimed by the manufacturer. Figure 3.9 shows a plot from HiTRAN-PC, a atmospheric-modeling software code described in the cw measurements section below, of the water vapor absorption lines within the tuning range of the ECDL/TA transmitter system. The wide tunability of this transmitter allows it to access any of the water vapor absorption lines in this region, giving it an unprecedented ability to choose the best absorption line for the given environmental conditions, which is a significant improvement over existing low-power water vapor DIAL systems.

The biggest advantages to using these commercial tapered amplifiers is that they are easily available (although expensive) and work well at the necessary wavelength,



Figure 3.7: A picture of the Sacher Lasertechnik Pilot driver used to control the tapered amplifier in the horizontal tuning experiments.

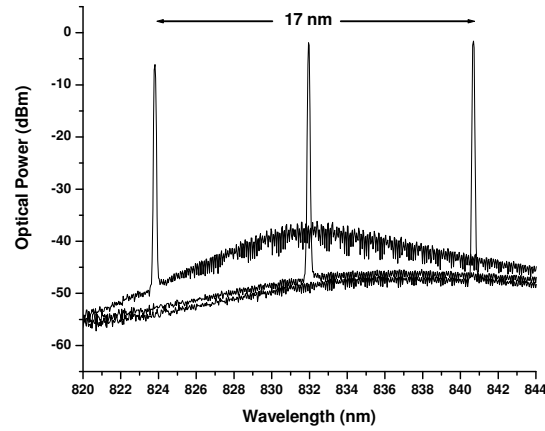


Figure 3.8: A plot of the tuning of the laser system. This is shown by three overlaid plots of the optical power of the injection seeded amplifier (attenuated to avoid damaging the OSA). The ECDL was tuned mechanically by adjusting the retroreflective prism to 824 nm (832 nm, 841 nm) and was used to seed the amplifier. The spectral output of the amplifier is controlled by the spectral properties of the injection seeded ECDL laser.

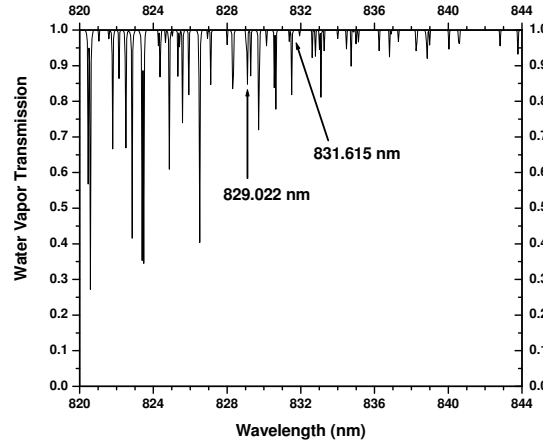


Figure 3.9: A plot of the horizontal path transmission calculated using HiTRAN-PC through a 1 km path length as a function of wavelength accessible by the tunable ECDL shown in figure 3.8. The absorption features are due to water vapor.

$\sim 830$  nm. The first major drawback is that they are typically difficult to align with the seed laser beam. Alignment requires that the seed beam be tightly collimated and horizontally polarized with respect to the TA input. Correct seeding requires precise alignment with the amplifier gain region, and typically required two independent mirrors for beam steering. New TA models, such as the second TA used in the DIAL system described in chapter 5, have a 1 mm longer gain region and thus are more difficult to align.

The second, and more important, major drawback to these tapered amplifiers is that pulsing them at the speeds necessary for DIAL measurements has so far proven unreliable. Several techniques were tried in an attempt to pulse the tapered amplifier. The TA itself has a pulsing option using external modulation, but the maximum rate that the amplifier could be cycled on and off was only 10 kHz, corresponding to a pulse length of  $100 \mu s$  (range resolution of 15000 meters), much too long for the range resolutions required in the DIAL experiment. A cycling rate of at least 1 MHz was

required to achieve pulse lengths of  $1\ \mu s$  (range resolution of 150 meters) or less. An attempt was made to pulse the TA using a different current driver (Directed Energy PCX-7410) in place of the Pilot driver. The Directed Energy driver has the capability to create sub-microsecond pulses at 50 kHz and beyond. Unfortunately, the electronics within the TA could not be changed, and apparently are not optimized for pulses shorter than about  $10\ \mu s$ . The results of these tests are shown in figure 3.10. The output pulse shape created by this method is not temporally square and is in fact unpredictable pulse-to-pulse, which would make data inversion of a DIAL signal more difficult. The power of the output pulse was seen to decrease rapidly as the pulse length was made shorter than  $10\ \mu s$ , disappearing almost completely below  $4\ \mu s$ . The pulse with a width of  $4\ \mu s$  is probably uniform enough temporally and would still provide reasonable power for an atmospheric experiment, but the pulses are not short enough to provide scientifically meaningful spatial resolutions. Another method of pulsing the cw beam would have to be found, and is described in the next section.

It should be noted that frequency chirp experiments following the method of *Repasky and Carlsten* (2000) were done with the PCX-7410 pulsing the TA at 10 kHz with  $10\ \mu s$  pulses to determine if the amplifier output was changing in frequency while being pulsed. Such a frequency change, or chirp, if too large, would render the transmitter useless for water vapor DIAL work, since frequency accuracy is critical to the DIAL technique. These experiments showed that the upper limit for frequency chirp in the DIAL transmitter was measured to be  $110.637 \pm 5.636$  MHz. The allowable chirp for a DIAL transmitter to keep errors below 3% for laser properties according to *Bösenberg* (1998) is  $\pm 161$  MHz at 830 nm, so at least for these pulsing conditions the DIAL transmitter's frequency chirp is within allowable tolerances. Frequency chirp at shorter pulse lengths should not be an issue because the amplifier is being seeded

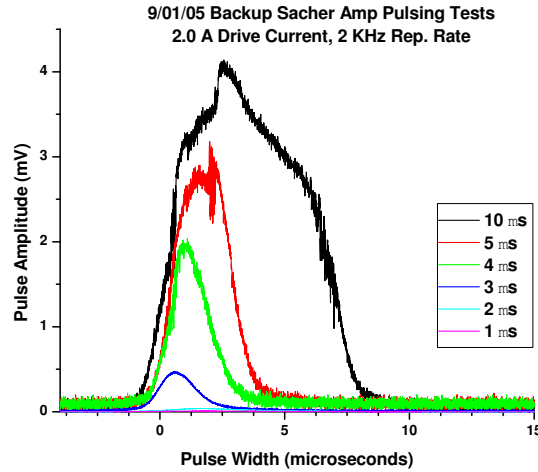


Figure 3.10: A plot of the pulsing characteristics of the Sacher Lasertechnik tapered amplifier. Faster pulses also have reduced output amplitudes, disappearing almost completely below  $4 \mu s$ , much too slow for use in the DIAL system.

by a cw ECDL source and its optical properties follow that of the ECDL. Still, the experiments should be repeated in the future if a way to pulse the TA directly with  $1 \mu s$  or shorter pulses is found, since the chirping characteristics might change as the pulse length gets shorter and the repetition rate increases.

Acousto-optic Modulator (AOM) When pulsing the TA directly failed, the next option was to use a mechanical chopper wheel located after the TA. Unfortunately, no commercial chopper could be found that would allow pulse widths of  $1 \mu s$  or less. The next option, and ultimately the option that was chosen, was to use an acousto-optic modulator (AOM) made by Isomet (1205C-2, figure 3.11). The advantages to using an AOM include that there is no frequency chirp in the transmitted beam and each pulse is a near-perfect square shape in time, as shown in figure 3.12. The drawback is that only about 66% of the light input to the AOM is transmitted through it into a pulsed beam, reducing the transmit power of an already low-power system.



Figure 3.11: A picture of the acousto-optic modulator (AOM) used to pulse the cw laser beam. The entrance aperture is visible on the side, below the “5” in 1205C-2.

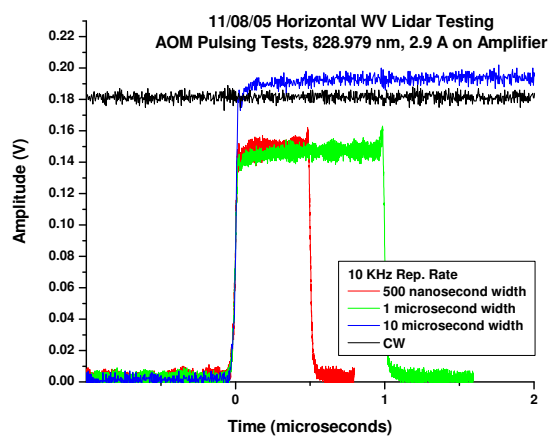


Figure 3.12: A plot of the pulsing characteristics of the AOM. Note the very clean square-wave shape of the output pulses.



Figure 3.13: A picture of broadband beam samplers. Image courtesy of Newport.com (<http://www.newport.com>).

Reference Power Meters and Beam Splitter To make the reference power measurements, the transmit beam was passed through a Newport Broadband Beam Sampler (figure 3.13) that reflected  $\sim 4\%$  of the light to a detector. The beam sampler was wedged in shape and anti-reflection-coated for light at 830 nm to avoid interference effects in the beam.

Several different types of detectors were used to make the reference power measurements before finally settling on the Newport 1830c optical power meter (figure 3.14). Newport 2001 detectors were used initially, but the active area was very small, making alignment a critical issue. Also, the Newport 2001 provided a voltage proportional to the light incident on its detector, which then had to be converted to a power measurement, and the Newport 1830c power meter provided a direct, calibrated measure of optical power. The 1830c was picked over the newer 1930c for a few reasons. First, it has a larger detector head allowing for more beam movement while still taking a valid power measurement. Second, it had a better response than the 1930c in the sense that the measurements did not vary much across the detector head, whereas they did on the 1930c. Third, the 1830c responded more consistently

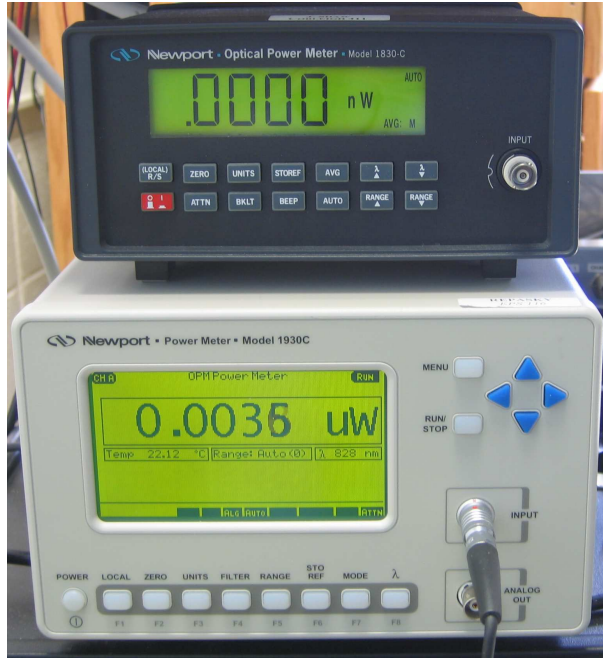


Figure 3.14: A picture of the Newport 1830c (top) and 1930c (bottom), used for diagnostics and reference power measurements in the horizontal tuning and vertical DIAL experiments.

to remote command and control. Being certain that the number being returned from the power meter is the correct measurement is critical for the DIAL measurements, and seemed to be more reliable with the 1830c. The 1930c was used primarily as a diagnostic tool, testing transmit powers along the beam path.

Telescope A commercial Schmidt-Cassegrain telescope (Celestron CGE1100) with a 28 cm diameter was used to collect the return photons. The telescope uses a folded design, with a primary mirror at the bottom of the telescope housing that reflects light to a smaller secondary mirror located in the middle of the entrance aperture. The advantage of this telescope configuration is that it is compact, but one disadvantage is that the secondary mirror blocks some of the aperture opening, effectively reducing the receiver area,  $A_r$ . A schematic of the telescope is given in figure 3.15. According to

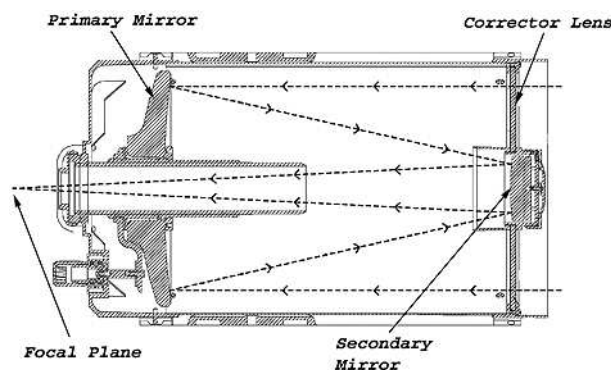


Figure 3.15: A schematic of a Schmidt-Cassegrain telescope. Image courtesy of Celestron.com (<http://www.celestron.com>).

the lidar equation, equation 2.1, the lidar return signal is directly proportional to the area of the receiving telescope. Therefore, larger telescope diameters allow for greater return signals. Basically, the telescope acts as a “light bucket” collecting as many photons as possible and focusing them for transport to a detector. While commercial telescopes are easy to purchase and use, one disadvantage is that their optical surfaces tend to be coated to maximize light transmission in the visible spectrum, and not in the near infrared where the DIAL experiments operate. This lowers the return signal, and cannot be avoided without putting custom coatings on the telescope optical surfaces, greatly increasing the purchase price. A plot of the Celestron “Starbright” coating is shown in figure 3.16.

Narrowband Filter An interference filter (Thorlabs, figure 3.17) with a 10-nm-wide band pass centered on 830 nm was used to exclude a large portion of background light being collected by the lidar receiver. It was placed directly on the entrance of the detector fiber to attempt to ensure that all light that would travel to the detector would first have to pass through the filter. 50% of the signal is lost due to the transmission of the filter, but with a photon-counting detector, as in these

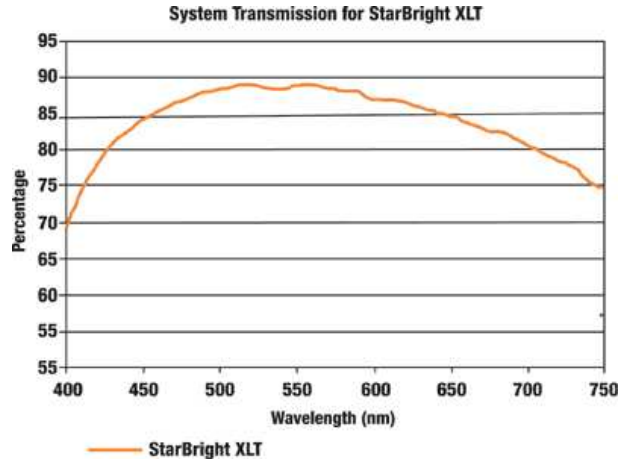


Figure 3.16: A transmission plot for the “Starbright” coating on the telescope used in the horizontal lidar tuning experiments. Image courtesy of Celestron.com (<http://www.celestron.com>).

experiments, blocking background light from room lights, street lights, and other sources is critical for obtaining an acceptable signal-to-noise ratio. An even narrower interference filter would be necessary for the vertical DIAL experiments.

Avalanche Photodiode (APD) Detector The detector (Perkin-Elmer SPCM-AQR-13-FC) is a self-contained single photon counting module avalanche photodiode (APD) requiring only a 5 V input and no external cooling. It is very compact and easy to use. The output of the detector is a TTL pulse for every detected photon over a range of 400 to 1100 nm. The advantage of using APD’s in low-power DIAL experiments is their high peak photon detection efficiency of  $\sim 74\%$  at 700 nm. The other primary detector that would work in this wavelength region is a photomultiplier tube (PMT), but their detection efficiency is much lower, perhaps  $\sim 20\%$  at most. The advantage of PMT’s is that they typically have large detector active areas, whereas the APD active area is  $170\ \mu\text{m}$  in diameter, making alignment critical. A GRIN lens is glued to the interior of the APD housing that projects an image of the fiber magnified by a factor of 1.4 onto the detector area. Since a  $650\ \mu\text{m}$  core diameter optical fiber carried



Figure 3.17: A picture of the type of narrowband filter used in the horizontal tuning experiments.

the received photons to the APD in these horizontal experiments, a large percentage of signal was lost due to overfilling of the detector active area. Again, this was not considered a problem as the hard targets produced more than enough return signal for these experiments. This would not be the case in a vertically-pointing lidar, however. The maximum count rate of the APD is nominally 15 Mc/s, with a dead time of 50 ns between pulses. If the count rate exceeds about 1 Mc/s, photons will go undetected because the APD does not have adequate time to reset between detections, and therefore a correction factor must be applied to the output.

APD's in photon counting mode are amazingly sensitive to all sources of light. Simply switching room lights on while the APD was active and exposed would risk damaging it. For this reason, one of the most critical design aspects of lidar systems using this detector, a lesson learned through many frustrating data runs, is that the APD must be isolated from all light sources to allow for accurate signal counts. If uncovered, even with room lights off, the APD is able to detect light from instrument



Figure 3.18: A picture of the avalanche photodiode (APD) detector.

displays, or light entering the room through door jams or cracks in walls. Great care was taken in the lidar experiments to completely isolate the APD in a sealed housing. Even the fiber carrying photons to the APD had to be wrapped in electrical tape because the APD was able to detect background photons from the room that penetrated the fiber cladding at some point between the fiber launch and the sealed detector.

Multi-channel Scalar (MCS) The TTL logic pulses that originate from the APD detector are then counted and binned in time by a multi-channel scalar (MCS, Stanford Research Systems SR 430, figure 3.19), which makes range resolution possible. This model of MCS was chosen because it is very easy to use and adjust and has a front-panel screen so that the return counts per bin can be observed in real time. The disadvantage to this type of MCS is that the display limits the speed of the instrument. The fastest rate at which the MCS could be triggered, and therefore the fastest rate at which we could pulse the laser, was 2272 Hz. For low-power lidar systems, one way to increase the return signal is to increase the laser repetition rate. For this reason, the vertical DIAL system would need a faster scalar card.



Figure 3.19: A picture of the Stanford Research Systems Multi-channel Scalar (MCS) with display screen used in the horizontal tuning experiments.



Figure 3.20: A picture of the three hard targets and their ranges used in the horizontal tuning experiments, taken from the roof of Cobleigh Hall at Montana State University, just above the roofport room where the measurements were made.

### Targets

Three buildings at different distances from the lidar were selected as hard targets for the tuning experiments. All distances to the targets were determined by GPS. The closest target was a metal exhaust stack on the roof of the MSU heating plant building, located 0.175 km away. The next two targets were similar in range: the upper-level of the MSU football stadium at a distance of 0.835 km away, and the second-story wall of the Museum of the Rockies at 0.855 km away. Each target was reasonably reflective so that the laser spot could be easily seen on the targets at night. Steam exhaust plumes from the Engineering and Physical Sciences (EPS) Building and the heating plant prohibited data collection on several occasions.

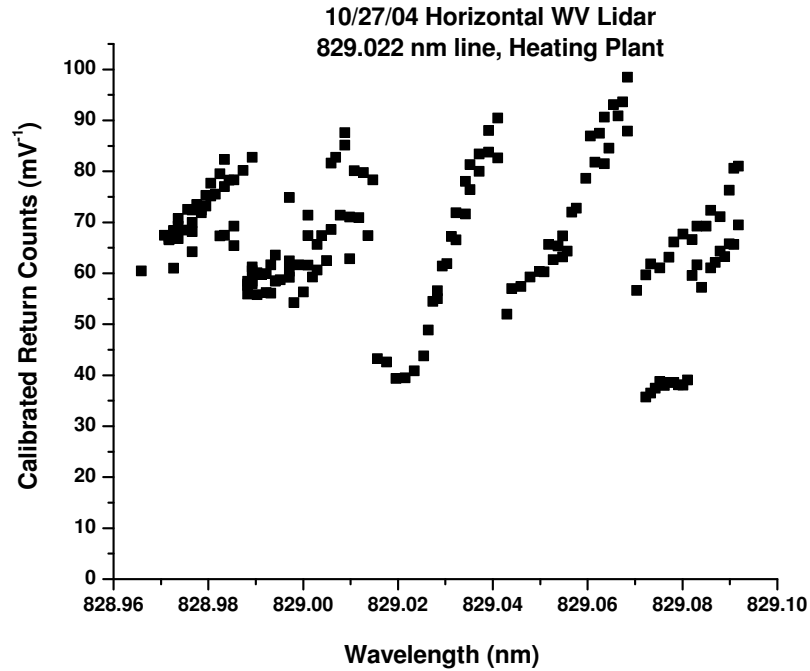


Figure 3.21: Early results from the horizontal tuning experiments. The data should show a water vapor absorption line centered at 829.022 nm with the counts rising to a steady value in the wings of the line.

### System Diagnostics

Early results with the horizontal experiments showed significant problems, as seen in figure 3.21. Months of iterating through system components, software versions, and testing was required to obtain accurate results.

P/I Curves The first tests that needed to be done characterized the health and behavior of the ECDL and TA. Figure 3.22 shows P/I curves for the ECDL and TA used in the horizontal experiments. These graphs show the increase in output power of each laser with increasing drive current. The ECDL was typically at a drive current 37 mA. The maximum output power of 8 mW was reduced by transmission through two optical isolators and a pick-off for the wavelength measurement, so typically only

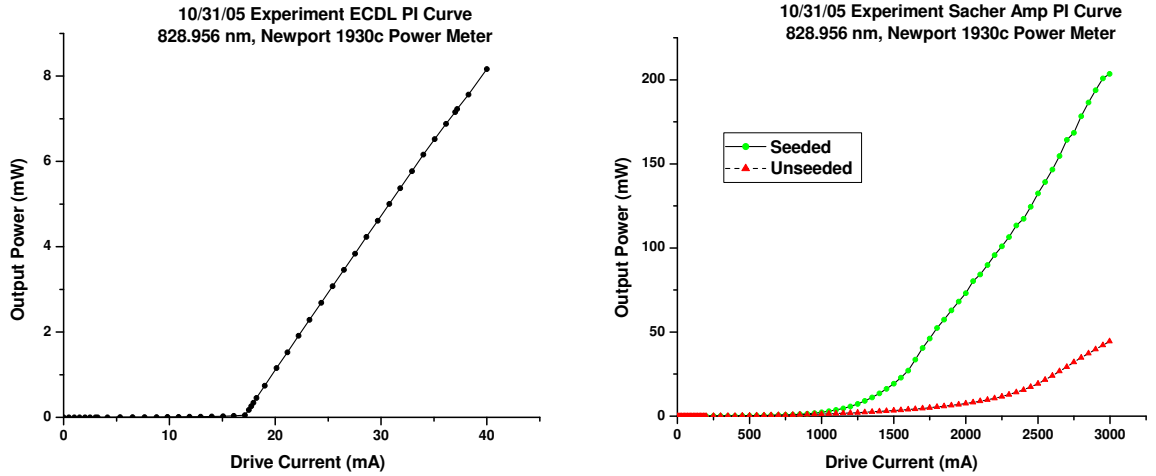


Figure 3.22: P/I curves for the ECDL and TA used in the horizontal tuning experiments.

5-6 mW was used to seed the TA. The P/I curve for the TA shows both the seeded and unseeded responses. Notice that when the TA is being seeded with only 5-6 mW, the maximum power output is only around 200 mW, well below the 500 mW output supposedly achievable if the TA is saturated with a seed power of  $\sim 20$  mW. The TA was typically driven with a current of 2500-2800 mA. Drive currents above that value drastically reduced the ability of the TA to follow the spectral qualities of the ECDL.

Linewidth and Tuning The next tests studied the ability of the TA to preserve the spectral qualities of the ECDL. Specifically, for the DIAL system to work, it had to be shown that the TA would maintain the narrow linewidth of the ECDL, and tune across wavelengths as the ECDL tuned. Figure 3.23 shows traces of the ECDL and TA output spectrum taken on an OSA. The high quality of the ECDL can be seen, with a narrow linewidth and sidemode suppression of greater than 30 dBm. The broad output spectrum of the TA is evident in the unseeded case. The power in this broad spectrum is forced into a narrow linewidth when seeded by the ECDL.

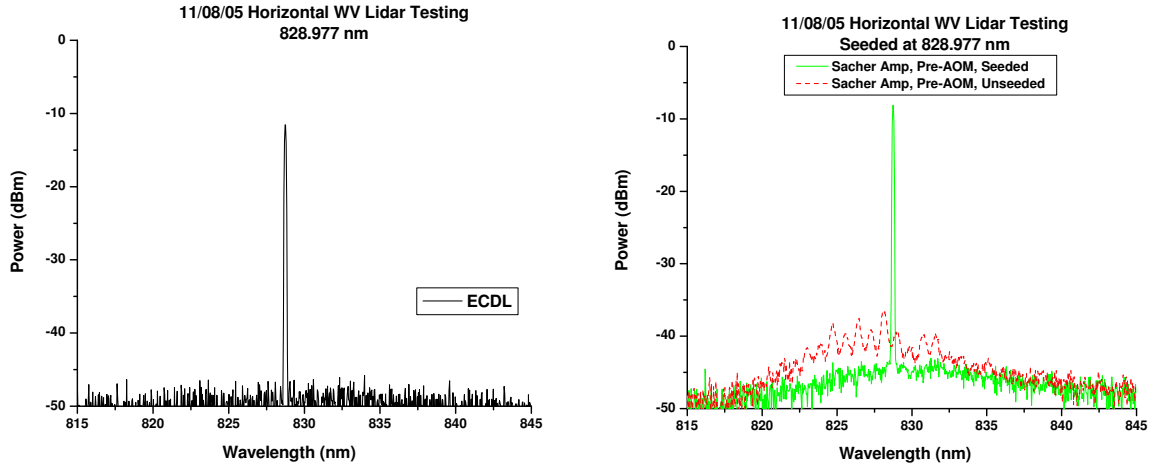


Figure 3.23: Optical spectrum analyzer traces for the ECDL and TA used in the horizontal tuning experiments.

Testing the tuning of the system was done by measuring the wavelength of the ECDL output and comparing that to the wavelength of the TA output as the ECDL tuned. A ratio of the amplifier wavelength and the ECDL wavelength was computed and should be very close to 1 if the TA is following the tuning of the ECDL. Figure 3.24 shows this to be the case. The ratio between the two wavelengths were identical to within the uncertainty of the wavemeter,  $\pm 0.1$  pm.

Reference Power Measurements The hardest problem to solve with the horizontal tuning experiments was accurately measuring and accounting for the fluctuations in the system's transmitted power. The optical power transmitted from the amplifier fluctuated by perhaps as much as 30% as the gain region heated up and changed size, changing the mode structure of the output radiation. These fluctuations were very pronounced when the amplifier was initially powered on, but calmed down considerably as the temperature came to an equilibrium. The power still fluctuated predictably as the ECDL tuned. Tests were done to verify that the ECDL did not

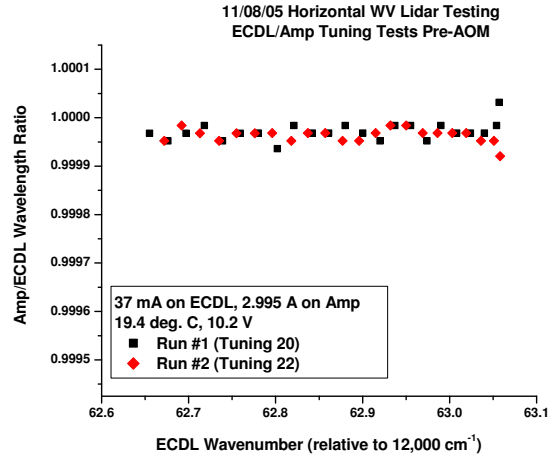


Figure 3.24: A plot of the ratio output wavelength of the amplifier to the output wavelength of the ECDL. The wavelengths agree to within the error of the wavemeters.

show the same power fluctuations. The results of the tests are shown in figure 3.25, showing the relatively constant power of the ECDL versus the power hops of the TA as the ECDL is tuned.

These power fluctuations are not a problem for the DIAL experiment as long as they can be monitored and normalized out of the return signal to ensure that any changes in return signal are due to atmospheric, and not laser, effects. As described in the reference power meters section above, the reference power detector was changed from a Newport 2001 solid-state detector to a Newport 1830c optical power meter to give a better response. One problem with the 1830c power meter, though, is that it does not seem to have the capability to clear the memory buffer completely. When a power measurement is made, it is stored in an internal memory buffer until read remotely by the laptop. Even after a “clear memory” command is sent to the meter, it will not erase the last power measurement that was made. Thus, after gaps in data taking, such as during laser tunings, the first reference power reading was wrong and had to be manually removed from the final data.

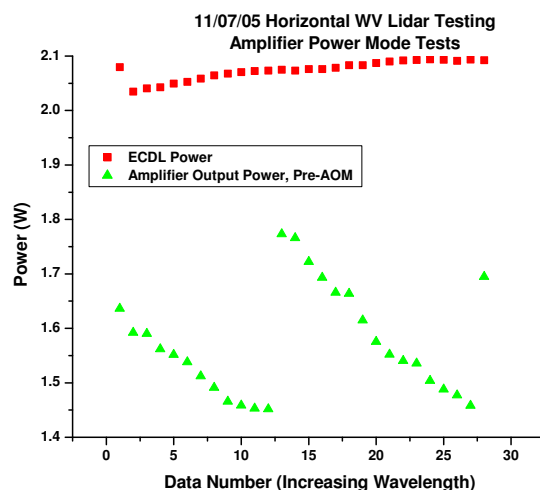


Figure 3.25: A plot showing the power modes of the tapered amplifier. As the ECDL tunes, the power output of the TA changes drastically, necessitating normalization of the return data with transmit power.

Ways to minimize the error in reference power measurements were found through several iterations of the operational software and experiment. Initially, the reference power was only measured once, before each data point was taken. This was found to be inadequate as the power would drift across the time needed to take a measurement, especially during the pulsed experiments where each data point was averaged for 100 seconds. To account for this, the reference power was measured before and after the data collection time to average out any output power drifts that might occur while data are being collected. Both reference powers, the return signal counts in the target bin, and the laser frequency were recorded to a data file at one wavelength after which the computer tuned the laser by adjusting the voltage applied to a piezo-electric tuner within the ECDL. Another software fix was to build in a “settle time” to allow the lasers to equilibrate for 5 seconds after each tuning period. This helped alleviate many of the power drifts. A hardware fix involved installing metal heat sinks underneath the amplifier to help dissipate heat. This, too, made a large difference in the amount

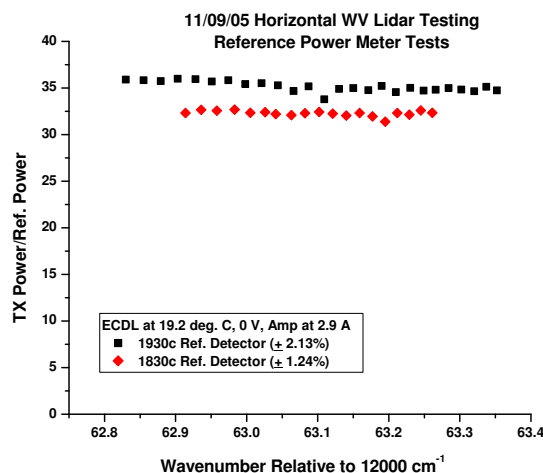


Figure 3.26: A plot showing how the reference power measurement actually tracks the transmit power of the horizontal system. Note that the Newport 1830c is more accurate.

of fluctuations that were measured. Many tests were done to ensure that the power fluctuations were indeed being normalized out of the return signal. The results of one such test are shown in figure 3.26. This graph shows the results of using the 1830c or the 1930c as the reference power meter, and comparing what they measure to the the actual measured transmit power through a ratio. Each line should be flat if the power fluctuations are fully removed. Both meters do a decent job, but the 1830c was consistently more accurate.

### CW Measurements

The first water vapor measurements were done with the laser transmitter operating in a cw mode, aimed at the hard targets described above. The outside air temperature and relative humidity were measured using a digital psychrometer-hygrometer (Mannix SAM990DW). About one hour was needed to fully tune and collect data across a water vapor line, taking a transmission measurement at typically over one

hundred wavelength points. Vertical DIAL systems will only need to collect return counts at two wavelengths, instead of scanning across wavelengths as in these tuning experiments. The LabVIEW software that controlled the experiment first recorded the laser wavelength from a wavemeter, then recorded the reference power of the transmitted beam, followed by triggering the MCS and recording the photon counts from it, and finally tuning the diode wavelength by adjusting the PZT voltage.

Measured and calculated relative atmospheric transmission spectra near 829.02 nm are plotted as a function of wavelength in figure 3.27 (normalized to 100% in the wings, where water vapor absorption is essentially zero). The measured transmission is determined from a ratio of the return signal with the transmitted power to compensate for the changing optical power of the laser transmitter as it is tuned. The closed (open) circles represent the measured transmission as a function of wavelength for a total path length of 1.71 km (0.35 km), and the solid (dashed) line represents the theoretical spectral transmittance calculated with HiTRAN-PC, a atmospheric-modeling software code that uses the HiTRAN 2000 database. HiTRAN-PC was developed by Dr. Dennis Killinger's group at the University of South Florida Laboratory for Laser Atmospheric Studies and is available through Ontar Corporation at 9 Village Way, North Andover, MA 01845-2000, USA (ph. 1-508-689-9622). The measured temperature of 12° C (4° C) and relative humidity of 47% (48%) were used in these calculations. The laser was tuned over 50 GHz for both of these measurements and an absorption feature at 829.022 nm is clearly evident, while a second weaker absorption feature at 829.055 nm is easily resolved for the 1.71 km path length.

Measured and calculated relative atmospheric transmission spectra near 831.615 nm are plotted as a function of wavelength in figure 3.28. The solid circles represent the measured atmospheric spectral transmission wavelength, while the solid line represents the theoretical predictions. The measured temperature of 7.3° C and relative

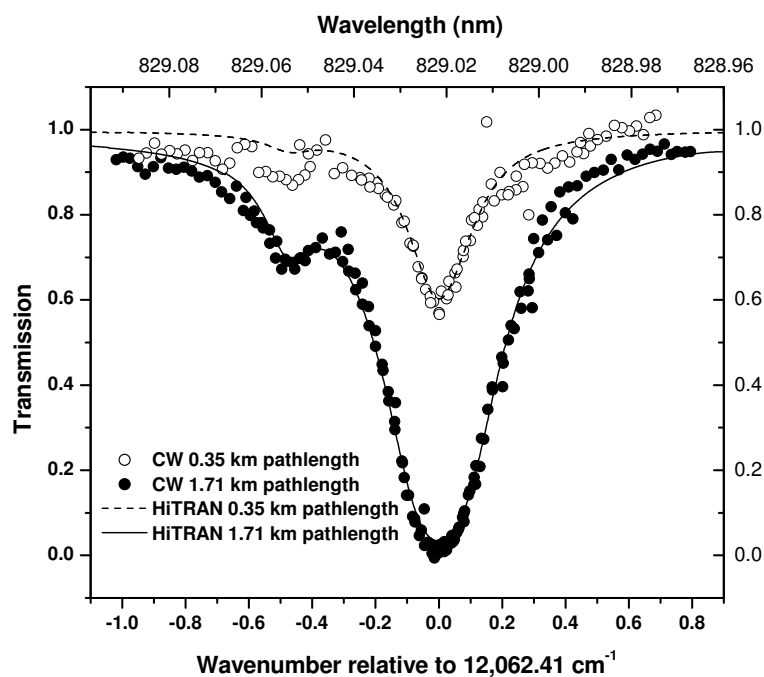


Figure 3.27: A plot of the transmission through the atmosphere as a function of wavelength near 829.02 nm. The closed (open) circles represent measurements made for a 1.71 km (0.35 km) path length. The solid (dashed) line is a theoretical calculation using HiTRAN-PC with the measured temperature and humidity used in the modeling.

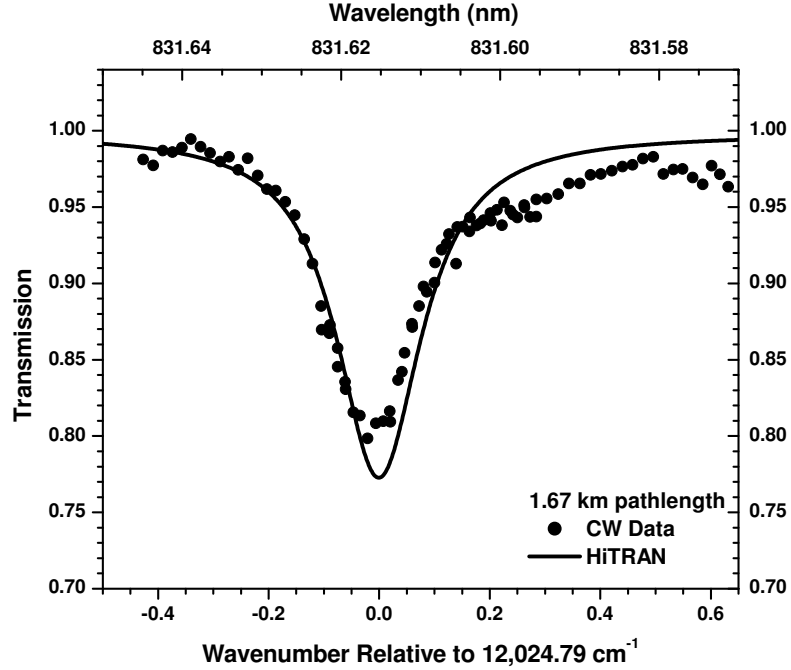


Figure 3.28: A plot of the transmission through the atmosphere as a function of wavelength near 831.62 nm. The closed circles represent measurements made for a 1.67 km path length. The solid line is a theoretical calculation using HiTRAN-PC with the measured temperature and humidity used in the modeling.

humidity of 50% were used in these calculations, made for a path length of 1.67 km.

#### Preliminary Pulsed Measurements

A comparison of the cw and pulsed operation of the laser transmitter was carried out for the absorption line near 831.615 nm. A plot of the relative atmospheric spectral transmission is shown in figure 3.29.

The open circles represent the cw measurements as described above while the filled circles represent the pulsed measurements. For both sets of measurements the ECDL laser was operated in a cw mode and pulsing was achieved by supplying a square pulse of current to the tapered amplifier. The pulse duration was 10  $\mu s$ , limited by

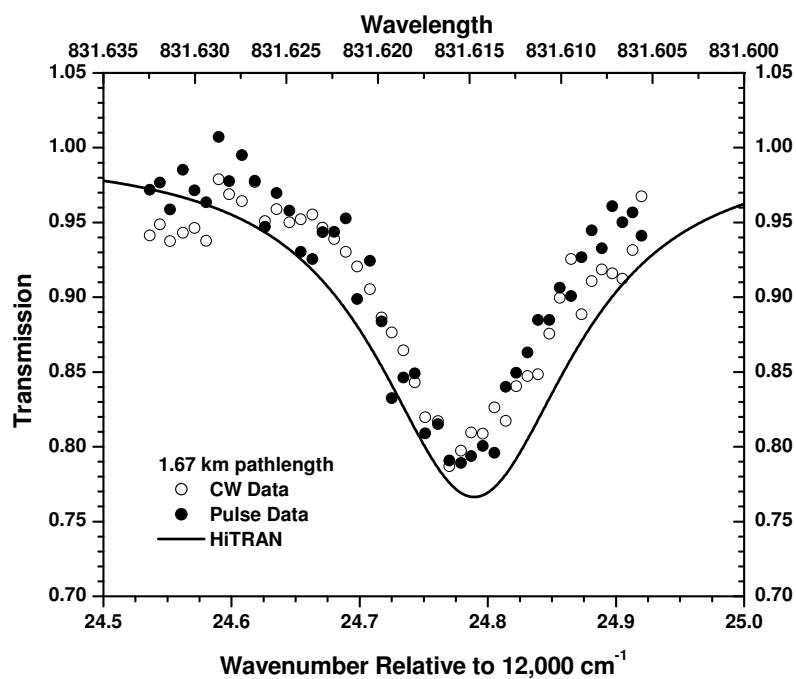


Figure 3.29: A plot of the atmospheric transmission as a function of wavelength. The open circles represent measurements made with a cw laser transmitter while the filled circles represent measurements made with a pulsed laser transmitter. The solid line represents the results of a HiTRAN-PC calculation for a 1.67 km horizontal path calculation.

the bandwidth of the current-driver electronics, which corresponds to a 3-km light path in air. Therefore, range resolving was not possible for the 1.67-km path in these preliminary pulsed measurements. The goal was to demonstrate the validity of pulsing the tapered amplifier as a DIAL transmitter.

Although these initial measurements employed a pulse repetition rate of 10 kHz and average optical power of only 18 mW, it was still possible to collect enough return signal by accumulating about 2000 pulses at each frequency. Good agreement between the pulsed and cw data is seen in figure 3.29, in which the solid line represents the radiative transfer calculation for a 1.67 km horizontal path at a temperature of 7.8° C and a relative humidity of 52%. This confirms the capability of this transmitter to maintain its high-quality characteristics during pulsed operation.

### Pulsed Measurements

After the cw and preliminary pulsed measurements, faster pulsed absorption measurements were taken by this system on three water vapor absorption lines, 829.022 nm, 831.615 nm, and 831.850 nm, at varying distances using the AOM. Data taken on the 831.615 nm absorption line proved to be too weak to be reliable and so the lidar was coarse-tuned to the slightly stronger 831.850 nm line instead, demonstrating the powerful flexibility of a system able to tune to several absorption lines. Pulses 500 ns wide, leading to 75-m-long rangebins and average pulse energies of 50 nJ per pulse, were transmitted at a repetition rate of 500 Hz. The repetition rate was limited by the data collection speed of the MCS. Signal averaging of typically 100 seconds was used to increase the return signal and smooth out short-timescale variations. An average of the off-line data was taken and used to normalize the entire data spectrum.

Data sets from two water vapor lines compared to HiTRAN predictions illustrating

the system tunability are shown in figures 3.30 and 3.31. Figure 3.30 shows tuning data taken across the 829.022 nm water vapor line at pathlengths of 1.71 km and 0.35 km. Figure 3.31 shows tuning data taken across the 831.850 nm water vapor absorption line at pathlengths of 1.67 km and 0.35 km. The varying pathlengths can be thought of as equivalent to the system response to varying relative humidities, as the absorption lines would become more or less pronounced depending on the water vapor density present in the atmosphere. The temperature and relative humidity measurements were made by a weather station located about 5 meters above the lidar and were averaged over the typically 1 hour or more needed to take all of the data points.

### Conclusions

Taken together, the figures from the pulsed measurements show the capability of the ECDL/TA transmitter to selectively probe different water vapor absorption lines depending on current atmospheric conditions. The experimental results, taken over many months and 46 night data runs, show that a DIAL system utilizing this ECDL and tapered amplifier combination will have an unprecedented ability to select which water vapor lines to scan depending on the prevailing atmospheric conditions. With the transmitter fully tested and verified, the next step was to select a water vapor absorption line to use in the DIAL experiments and begin designing, building, and testing the DIAL.

Horizontal WV Lidar  
 829.022 nm line  
 500ns pulses, 640ns bins, 500 Hz rep. rate, 100 sec. ave.

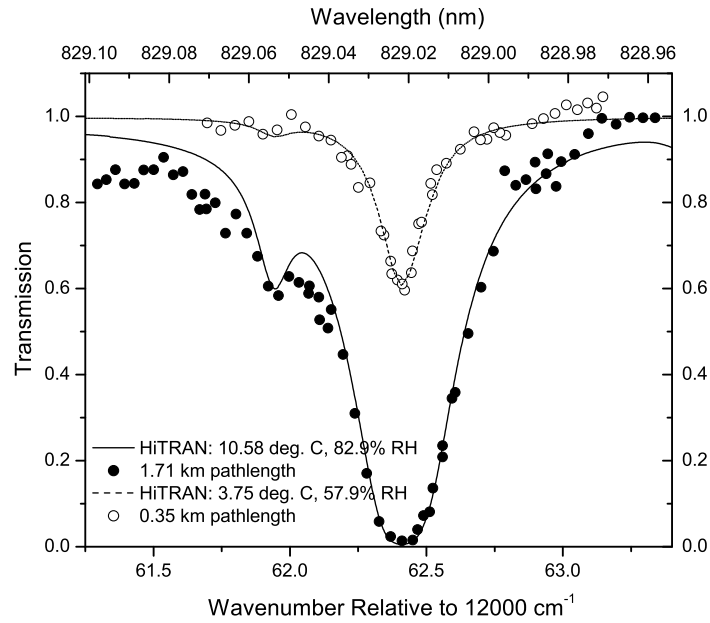


Figure 3.30: A plot of the relative transmission through the atmosphere as a function of wavelength near 829.022 nm. The open (closed) circles represent measurements made for a 0.35 km (1.71 km) path length. The solid and dashed lines are theoretical calculations using HiTRAN-PC with the measured temperature, humidity, and path length.

Horizontal WV Lidar  
 831.850 nm line  
 500ns pulses, 640ns bins, 500 Hz rep. rate, 100 sec. ave.

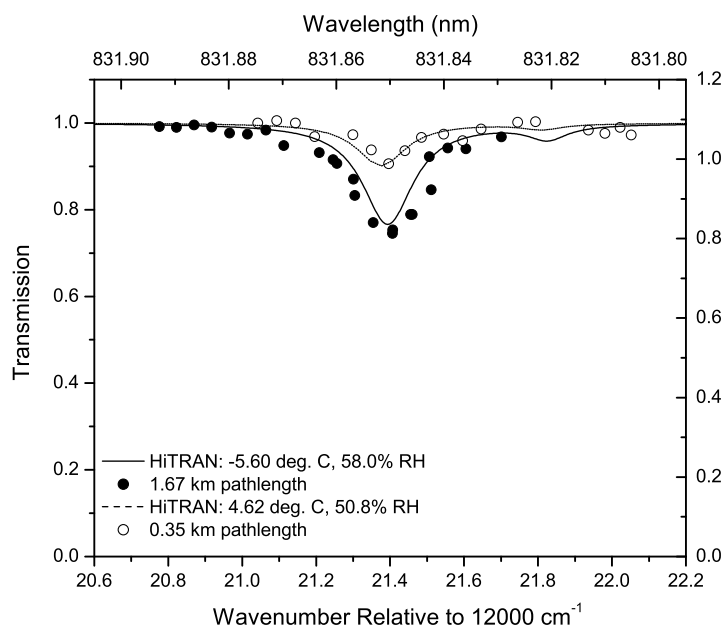


Figure 3.31: A plot of the relative transmission through the atmosphere as a function of wavelength near 831.850 nm. The open (closed) circles represent measurements made for a 0.35 km (1.67 km) path length. The solid and dashed lines are theoretical calculations using HiTRAN-PC with the measured temperature, humidity, and path length.

## CHAPTER 4

## WATER VAPOR ABSORPTION LINE SELECTION

Theory

Selection of a water vapor absorption line for use in DIAL measurements is of critical importance to the accuracy of the measurement. Three sources of error need to be considered when selecting a line. First, absorption line strengths, and therefore line shapes and absorption cross sections, can be strong functions of temperature, causing errors in the measurement due to the uncertainty in temperature as the laser pulse propagates through the atmosphere. Second, the optical depth produced by the absorption line must be considered, as absorption lines can either be too strongly absorbing, resulting in too low of a return signal, or too weak, resulting in not enough difference between the on- and off-line return signals. Third, the presence of other absorption features near to the absorption line being used can cause errors to be made in the absorption cross section measurement of this line, unless these other features are properly accounted for. A balance must be struck between the three criteria of temperature sensitivity, optical depth, and nearby absorption features when finding an appropriate water vapor absorption line for DIAL measurements.

The procedure for selecting a water vapor absorption line described below closely follows the methods of *Browell et al.*, 1991. Their analysis covered absorption lines in the 720 *nm* region, and I have applied a similar analysis to absorption lines in the 824-841 *nm* region. More recently, *Ambrico et al.*, 2000 showed results for temperature sensitivity analysis in much of the near infrared for a greater number of molecules

than just water vapor. I compare my results to theirs below.

### Line Selection Criteria

#### Temperature Sensitivity

Water vapor absorption line cross sections in the lower troposphere can be described by one of three line shape profiles, depending on the dominant broadening process, which is a function of pressure and hence altitude in the atmosphere. In any case, the temperature-dependent line strength,  $S$ , is given by (*Browell et al.*, 1991)

$$S(T) = S_0 \left( \frac{T_0}{T} \right)^{3/2} \left\{ \frac{1 - \exp[-hc\nu_0/(kT)]}{1 - \exp[-hc\nu_0/(kT_0)]} \right\} \exp\left( \left( \frac{hc}{k} \left[ \frac{1}{T_0} - \frac{1}{T} \right] E'' \right) \right), \quad (4.1)$$

where  $S_0 [cm^{-1}/(mol \cdot cm^{-2})]$  and  $T_0 [Kelvin]$  are reference values of line strength and temperature,  $h [6.626 \times 10^{-34} Joule \cdot s]$  is Planck's constant,  $c [2.998 \times 10^8 m/s]$  is the speed of light in vacuum,  $\nu_0 [cm^{-1}]$  is the line center wavenumber,  $k [1.38 \times 10^{-23} J/(mol \cdot K)]$  is Boltzmann's constant, and  $E'' [cm^{-1}]$  is the energy needed to transition between the ground state and a specific excited state. As is typical in spectroscopy, the energy  $E''$  is normalized by  $hc$  and given in wavenumbers. For absorption lines close to the surface ( $< 2 km$  above sea level), atmospheric pressure, or collisions between molecules, is the dominant broadening process and the absorption line profile can be described by the Lorentzian profile. The Lorentz linewidth, defined as the half width of the line at half of its maximum amplitude (HWHM, in  $cm^{-1}$ ), is given by

$$\gamma_L = \gamma_0 \left( \frac{P}{P_0} \right) \left( \frac{T_0}{T} \right)^\alpha, \quad (4.2)$$

where  $P [atm]$  is the pressure and  $\alpha [unitless]$  is the linewidth temperature depen-

dence parameter (*Browell et al.*, 1991; *Liou*, 2002). Again,  $P_0$ ,  $T_0$ , and  $\gamma_0$  are initial values. The cross section  $\sigma_0 [cm^2]$  at line center is (*Browell et al.*, 1991)

$$\sigma_0 = \frac{S}{\pi\gamma_L}. \quad (4.3)$$

Here, the subscript 0 denotes that the cross section value is taken at line center,  $\nu_0$ , as opposed to some other wavenumber  $\nu [cm^{-1}]$ .

In the opposite case of high altitudes ( $> 50 km$  above sea level) where the pressure is low and intermolecular collisions are infrequent, the dominant broadening process will be Doppler broadening. This process arises due to the Maxwell-Boltzmann distribution of the molecular velocities, which creates Doppler shifts in the observed radiation frequencies. In this case, the absorption line profile can be described by the Gaussian profile and the Doppler linewidth (HWHM) is given by (*Browell et al.*, 1991)

$$\gamma_D = \left(\frac{\nu_0}{c}\right) \left(\frac{2kT \ln 2}{m}\right)^{1/2}, \quad (4.4)$$

where  $m [kg/molecule]$  is the mass of the water molecule. The absorption cross section is defined by a Gaussian function,

$$\sigma(\nu) = \frac{S}{\gamma_D} \left(\frac{\ln 2}{\pi}\right)^{1/2} \exp\left[-\frac{\ln 2(\nu - \nu_0)^2}{\gamma_D^2}\right], \quad (4.5)$$

where  $\nu [cm^{-1}]$  is the wavenumber at which the cross section is being calculated. At line center ( $\nu = \nu_0$ ) this cross section reduces to

$$\sigma_0 = \frac{S}{\gamma_D} \left(\frac{\ln 2}{\pi}\right)^{1/2}. \quad (4.6)$$

While pressure broadening is dominant at low altitudes ( $< 2 km$  above sea level)

and Doppler broadening is dominant at much higher altitudes ( $> 50 \text{ km}$  above sea level), effects of both broadening mechanisms can be seen in between these two extremes. In this case, a convolution of the Lorentz and Gaussian profiles is used, which is called a Voigt profile. The Voigt profile is given by

$$V(x, y) = \frac{\sigma(x, y)}{K} = \frac{y}{\pi} \int_{-\infty}^{\infty} \frac{\exp(-t^2)}{y^2 + (x - t)^2} dt, \quad (4.7)$$

where  $\sigma(x, y) [\text{cm}^2]$  is the absorption cross section,  $x = [(\nu - \nu_0)/\gamma_D](\ln 2)^{1/2}$ ,  $y = (\gamma_L/\gamma_D)(\ln 2)^{1/2}$ , and  $K = (S/\gamma_D)(\ln 2/\pi)^{1/2}$ .

Analyzing the temperature sensitivity of an absorption line then involves using these definitions to quantify how the measurement being made changes with temperature. With number density measurements, the number density error is given as the percent change in absorption cross section per unit temperature change, or

$$\frac{1}{dT} \frac{d\sigma_0}{\sigma_0} \approx \frac{1}{T - T'} \frac{\sigma_0(T) - \sigma_0(T')}{\frac{[\sigma_0(T) + \sigma_0(T')]}{2}}. \quad (4.8)$$

For mixing ratio measurements, *Cahen et al.* (1982) showed that the error depends on  $\sigma/T$  instead of just  $\sigma$ , and therefore the mixing ratio error is calculated by

$$\frac{1}{dT} \frac{d(\sigma_0/T)}{(\sigma_0/T)} \approx \frac{1}{T - T'} \frac{\sigma_0(T)/T - \sigma_0(T')/T'}{\frac{[\sigma_0(T)/T + \sigma_0(T')/T']}{2}}. \quad (4.9)$$

This also has the implication that absorption lines suitable for number density measurements are not suitable for mixing ratio measurements, and vice versa. For this reason, and knowing that the narrowband filters needed for each absorption line are expensive ( $\sim \$5000$ ), I chose to only select a line for number density measurements, leaving line selection for mixing ratio measurements to the interested reader.

A MATLAB program (voigt.m) was written to calculate the number density and

mixing ratio errors with respect to changes in temperature, pressure, and ground state transitional energies, according to equations 4.8 and 4.9. The goal of the error calculations was to repeat the analysis and figures of *Browell et al.* (1991) to verify that the algorithm used was correct before continuing with line selection. Reference values for the program were taken from the HiTRAN 2000 database and were:  $S_0 = 2.75 \times 10^{-23} \text{ cm}^{-1}/(\text{mol} \cdot \text{cm}^{-2})$ ,  $P_0 = 1.0 \text{ atm}$ , and  $T_o = 296.0 \text{ K}$ . Values in the HiTRAN 2000 database are specified for this temperature. All calculations were performed at line center, such that  $\nu_0 = \nu = 13785.0 \text{ cm}^{-1}$ . The pressure was input at the command line from the user. Calculations were performed at  $1.0 \text{ atm}$ ,  $0.5 \text{ atm}$ , and  $0.25 \text{ atm}$ . The values for  $\alpha$  and  $\gamma_L$  were taken from the HiTRAN 2000 database and plotted against  $E''$  to determine a linearly varying relationship. Figure 4.1 shows Figures 2 and 3 from *Browell et al.* (1991), as repeated by me using HiTRAN 2000 data for water vapor lines in the  $720 \text{ nm}$  region. The data used originally in these figures was measured, and therefore known to be reasonably accurate. I repeated the same graph techniques for water vapor lines between  $824 \text{ nm}$  and  $841 \text{ nm}$ , the tuning range of the lidar transmitter. Unfortunately, the values of  $\alpha$ ,  $\gamma_L$ , and  $E''$  are not known for all or maybe even most of the water vapor lines in this region, according to the HiTRAN 2000 database. Some values were missing, while others appeared to be just average values. An example of this is that  $\gamma_L = 0.68 \text{ cm}^{-1}$  was used for a majority of absorption lines throughout the database. Guessing that many of these were averages and not actual values, I only plotted values for water vapor absorption lines where  $\gamma_L \neq 0.68 \text{ cm}^{-1}$ . As can be seen in the lower graphs of Figure 4.1, the linear fits for the  $824 \text{ nm}$  to  $841 \text{ nm}$  region were both higher than for the  $720 \text{ nm}$  region. Since I could not verify that these linear fits were correct or were merely due to my bias in data selection, I used the fits from *Browell et al.* (1991) to calculate values for  $\alpha$  and  $\gamma_L$  based on  $E''$  values of 0 to  $500 \text{ cm}^{-1}$  in increments of  $50 \text{ cm}^{-1}$ .

The values used are specified in table 4.1.

|                      |          |          |          |          |          |          |
|----------------------|----------|----------|----------|----------|----------|----------|
| $E'' [cm^{-1}]$      | 0        | 50       | 100      | 150      | 200      | 250      |
| $\alpha$             | 0.79806  | 0.77542  | 0.7284   | 0.73015  | 0.70751  | 0.68488  |
| $\gamma_L [cm^{-1}]$ | 0.10235  | 0.09996  | 0.0976   | 0.09518  | 0.09280  | 0.090403 |
| $E'' [cm^{-1}]$      | 250      | 300      | 350      | 400      | 450      | 500      |
| $\alpha$             | 0.68488  | 0.66224  | 0.63960  | 0.61697  | 0.59433  | 0.57170  |
| $\gamma_L [cm^{-1}]$ | 0.090403 | 0.088014 | 0.085625 | 0.083235 | 0.080846 | 0.078457 |

Table 4.1: Values for  $E''$ ,  $\alpha$ , and  $\gamma_L$  as determined by the linear fit of Figure 4.1.

With the initial values specified, the values for  $\alpha$ ,  $\gamma_L$ , and  $E''$  were hard-coded into the program and incremented until data were taken at each  $E''$  value. The powerful matrix capability of MATLAB was used to do each computation at temperatures from 100 K to 500 K in 1 K segments. The program first calculates the Lorentz cross section, using equation 4.3, followed by the number density and mixing ratio errors for the Lorentz case using equations 4.8 and 4.9. Next, the pressure-dependent Lorentz line width and the Doppler line width, as defined in equations 4.2 and 4.4 were computed, allowing the Voigt function parameters  $x$  and  $y$  to be calculated. The Voigt function integral was then evaluated using a step-wise procedure, adding up the value of the integral in steps from one side of the function to the other. Surprisingly, the *int()* and *quad()* functions in MATLAB could not solve the seemingly simple Voigt function integral. The results of the custom step-wise procedure versus the MATLAB *int()* function are shown in Figure 4.2.

After the Voigt function integral is computed, the values for the line strength  $S$ , the Voigt function parameter  $K$ , and the Voigt function itself from equation 4.7 were computed. Then, using the relation in equation 4.7 of  $V = \sigma/K$ , the Voigt function cross section  $\sigma$  was found. Finally, this cross section was again used to find the number density and mixing ratio errors using equations 4.8 and 4.9. The results, combined into graphs separated by pressure, are shown in Figures 4.3 and

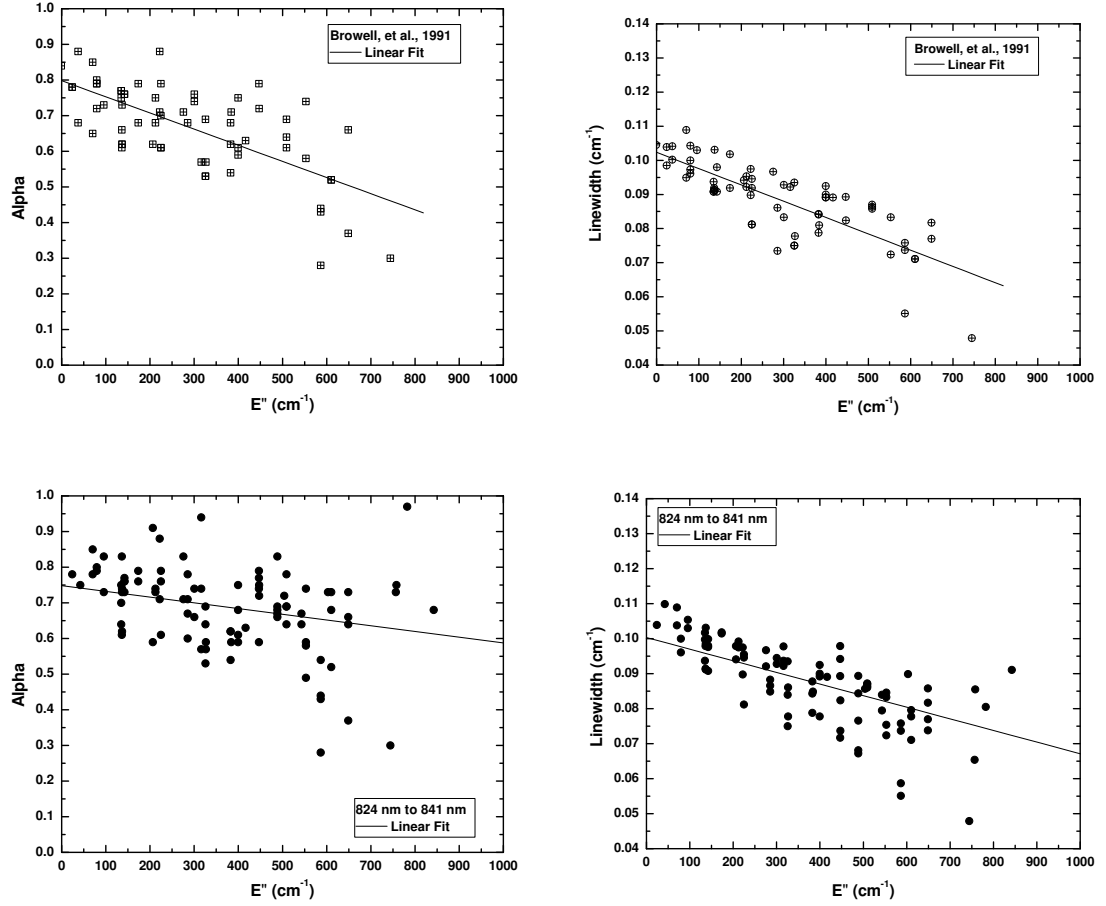


Figure 4.1: The top graphs are Figures 2 and 3 from *Browell et al.* (1991) showing linear fit relationships between the linewidth temperature dependence parameter  $\alpha$ , the Lorentz linewidth  $\gamma_L$ , and the ground state energy  $E''$  in the 720 nm region. These graphs are repeated here to show consistency between my method and that of *Browell et al.* (1991). The bottom graphs show the linear fit relationships between these same parameters in the 824 nm to 841 nm region.

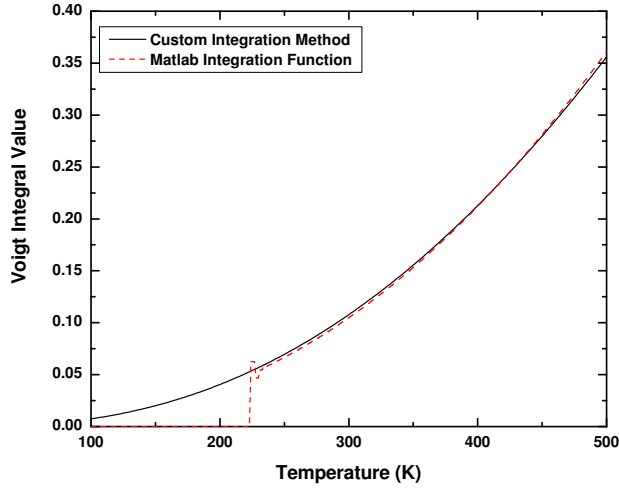


Figure 4.2: The MATLAB integration function could not solve the Voigt integral at low temperatures, sending the value of the integral to zero at a certain point. A custom integration method needed to be written to solve the integral down to 100 K.

4.4. The curves are in excellent agreement with those published in *Browell et al.* (1991), differing slightly because slightly different values of  $\alpha$  and  $\gamma_L$  (directly from the linear fits described above), and  $\nu_0$  were probably used, since the authors did not specify their exact values. Examining the three smaller-scale graphs of Figure 4.3 shows that the optimal  $E''$  limits for number density measurements that give error values of  $\pm 0.10\%/K$  between 200 K and 300 K for pressures changing from 1.0 atm to 0.25 atm are about  $125 - 225\text{ cm}^{-1}$ . My temperature sensitivity results, therefore, agree with those of *Browell et al.* (1991). Water vapor absorption lines with ground state transitional energies within this range will be acceptably temperature independent for number density measurements.

It should be noted here that the limits commonly stated in the literature for where pressure broadening or Doppler broadening are important are estimations at best. Unless it is known with certainty that measurements are being made well within either of those two limits, a Voigt function should be used for calculations

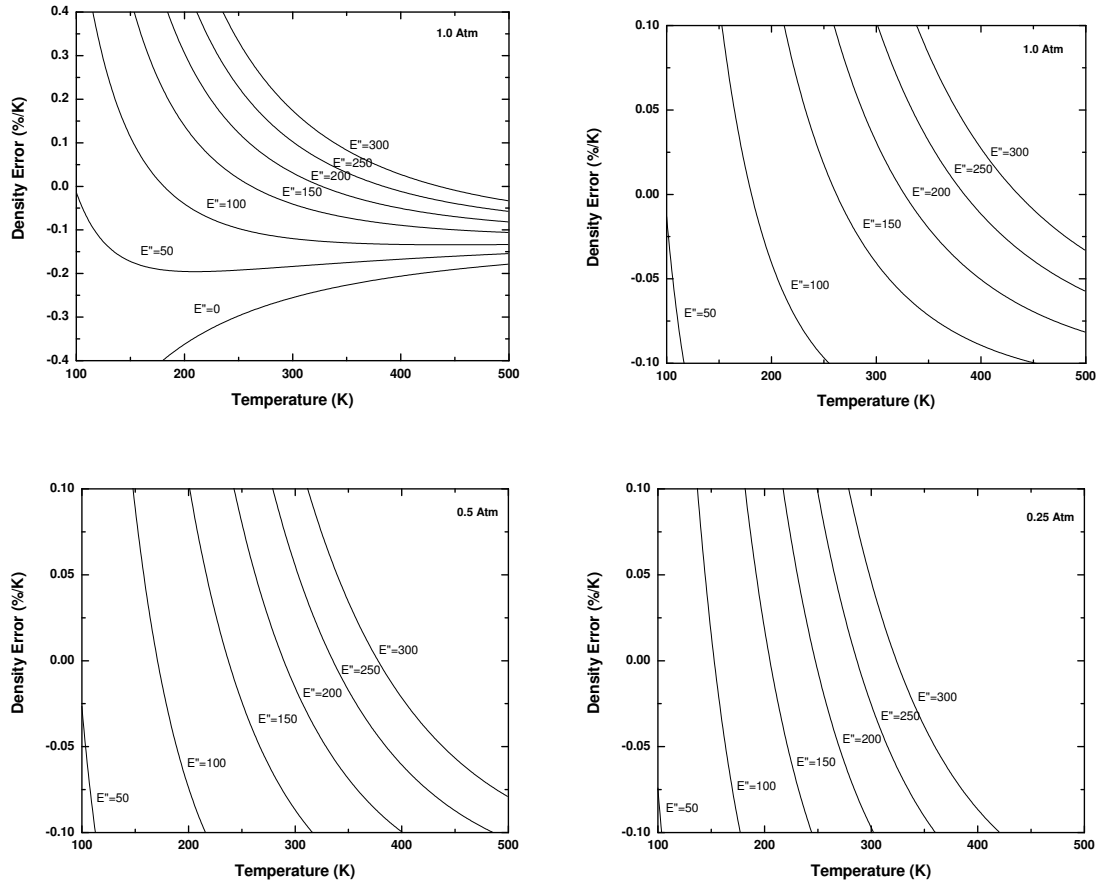


Figure 4.3: These figures show the number density error produced across a range of temperatures, pressures, and  $E''$  values, generated using my MATLAB Voigt profile calculator. They are nearly identical to Figures 4 and 5 from *Browell et al.* (1991), showing that the calculation method is valid. The top left graph shows the number density temperature sensitivity on a larger scale. The other graphs show the number density temperature sensitivity at 1.0 atm, 0.5 atm, and 0.25 atm pressures scaled to a  $\pm 0.10 \text{ \%}/K$  error.

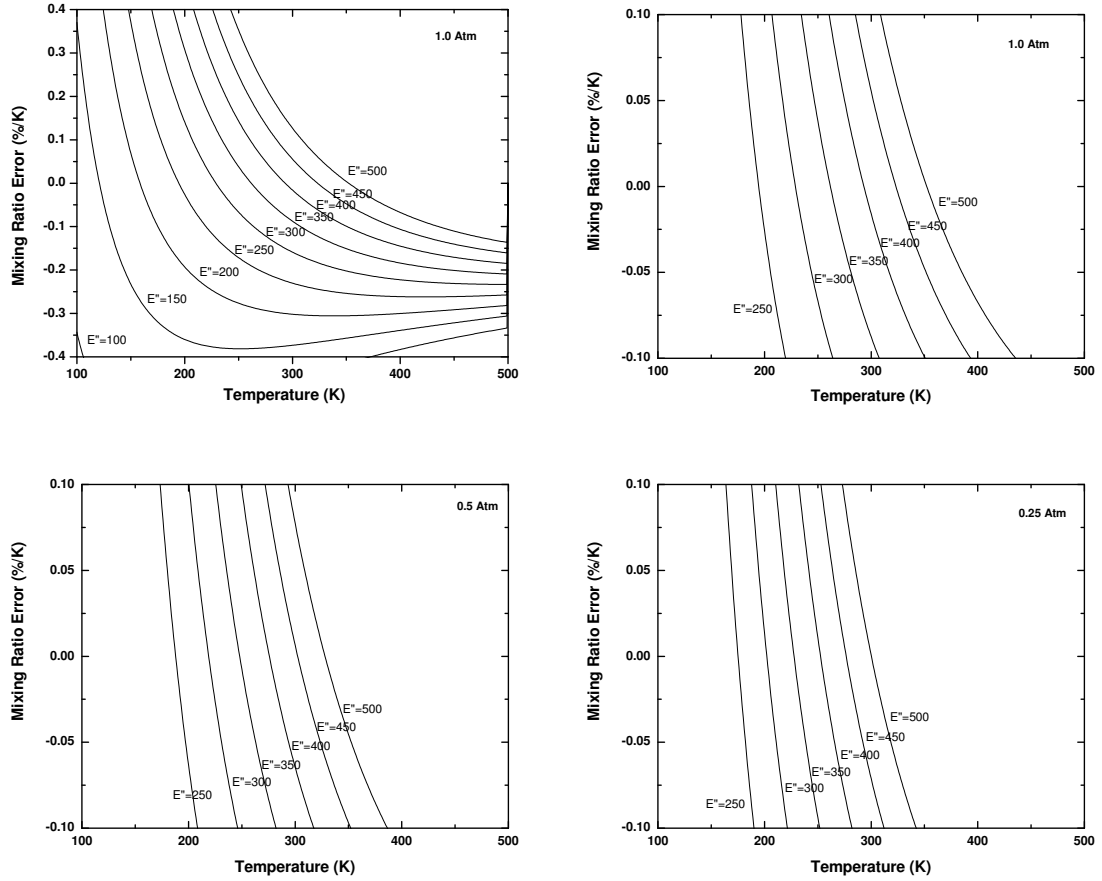


Figure 4.4: These figures show the mixing ratio error produced across a range of temperatures, pressures, and  $E''$  values, generated using my MATLAB Voigt profile calculator. They are nearly identical to Figure 6 from *Browell et al.* (1991). The top left graph shows the mixing ratio temperature sensitivity on a larger scale. The other graphs show the mixing ratio temperature sensitivity at 1.0 atm, 0.5 atm, and 0.25 atm pressures scaled to a  $\pm 0.10\%$ /K error.

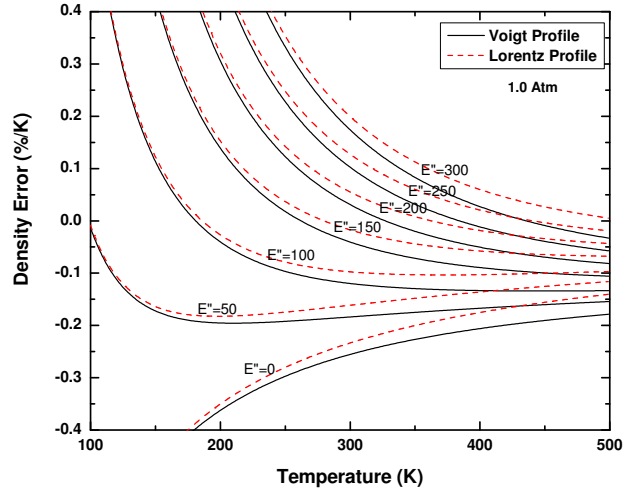


Figure 4.5: Deviation from the Voigt profile in the number density error calculations at 1.0 *atm* that would occur if a Lorentz profile were used.

if possible. Examples of errors that could be incurred if a Lorentzian line profile is incorrectly assumed are given in Figures 4.5 and 4.6. Figure 4.5 shows the deviation from the Voigt profile in the number density error calculations at 1.0 *atm* that would occur if a Lorentz profile were used. The error in the calculated density error could change by about 0.01 %/*K* depending on the atmospheric temperature. Figure 4.6 shows the deviation from the Voigt profile in the number density error calculations at 0.25 *atm*, where the error becomes much more apparent, changing by 0.1 %/*K* or more. Using a Voigt profile becomes especially important at high altitude locations, such as Bozeman, Montana, where the ground level air pressure is already less than 1.0 *atm*.

### Optical Depth

After temperature sensitivity, the next limiting factor in the absorption line selection procedure is the strength of the line, or more specifically, the optical depth it

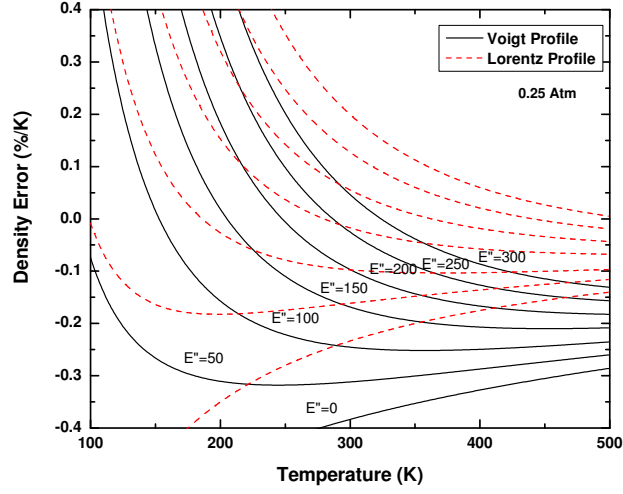


Figure 4.6: Deviation from the Voigt profile in the number density error calculations at 0.25 atm that would occur if a Lorentz profile were used.

produces. Optical depth (OD),  $\tau$  [unitless], is defined as

$$\tau = \int_0^R N \sigma dr, \quad (4.10)$$

where  $R$  [m] is the range of the measurement and  $N$  [molecules/cm<sup>3</sup>] is the number density of water vapor molecules. If the absorption line is too strong,  $\sigma$  will be relatively large compared to the off-line absorption, causing  $\tau$  to be too large and the on-line return signal to be too weak, since the signal goes as  $e^{-\tau}$ . Conversely, if the absorption line is too weakly absorbing,  $\sigma$  will be relatively small compared to the off-line absorption, causing  $\tau$  to be too small and the on-line return signal to be undifferentiable from the off-line signal return. Differential absorption lidar error analysis has shown that the optimal one-way value for  $\tau$  is 1.1 at the desired range (Remsberg and Gordley, 1978).

Because the optical depth is a function of the number density of water vapor

molecules, the optimal strength absorption line will be dependent on the geographic location of the measurement. Water vapor lines that are suitable for Bozeman, Montana, a relatively dry climate, would be unusable in a highly humid tropical region. Some *a priori* knowledge of the behavior of water vapor in the region of interest is required. For my analysis, I used archived temperature, pressure, and relative humidity data collected by the Optical Remote Sensor Laboratory's weather station located on the roof of Cobleigh Hall on the Montana State University campus from August 2005 through July 2006 (*Shaw*, 2006).

The number density of water vapor is calculated by first calculating the partial pressure of water vapor using the equation

$$p_{H_2O} = RH \times \left( \frac{6.11}{1013.25} \right) \times 10^{\left( \frac{aT}{b+T} \right)}, \quad (4.11)$$

where  $RH$  [unitless] is the relative humidity and ranges between 0 and 1,  $a = 7.5$ , and  $b = 237.3$ . The factors of 6.11,  $a$ , and  $b$  relate to saturated vapor with respect to liquid water, and would be slightly different if ice produced the vapor. The factor of  $1/1013.25$  converts the partial pressure from millibars to atmospheres (*Kyle*, 1991). From the partial pressure, the number density of water vapor can be calculated using the ideal gas law,  $p_{H_2O}v = nkT$ , where  $v$  [ $m^{-3}$ ] is the volume and  $n$  [unitless] is the number of molecules. Solving for the number density,  $N = n/v$ ,

$$N = \left( \frac{p_{H_2O}}{kT} \right) \times \left( \frac{1.01325 \times 10^5}{1.0 \times 10^6} \right) [cm^{-3}]. \quad (4.12)$$

Using equations 4.11 and 4.12, a monthly average water vapor mass density was computed for one year spanning the range of dates given above. The results are plotted in Figure 4.7.

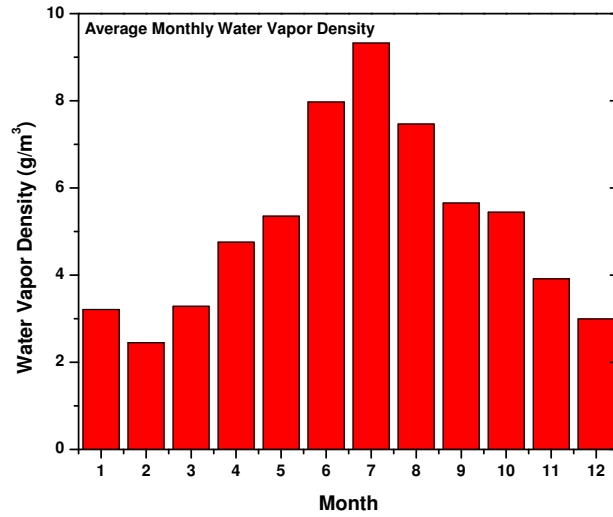


Figure 4.7: The average monthly water vapor density in Bozeman, Montana. The water vapor density was calculated using temperature, pressure, and relative humidity data collected by the Optical Remote Sensor Laboratory’s weather station on the roof of Cobleigh Hall at Montana State University between August 2005 and July 2006.

The average density of water vapor was then used in a MATLAB program to compute the monthly average OD using equation 4.10. The desired range was input by the user at the command line;  $2.0\text{ km}$  was used in my analysis. Water vapor lines being analyzed were limited to those within the acceptable bounds for  $E''$  as stated in section 4. The center wavenumbers of the most promising lines, which produced OD’s between 0.70 and 2.00 during five or more months of the year include:  $12060.1078\text{ cm}^{-1}$  (8 months),  $12074.5689\text{ cm}^{-1}$  (9 months),  $12078.817\text{ cm}^{-1}$  (7 months),  $12082.223\text{ cm}^{-1}$  (5 months), and  $12085.602\text{ cm}^{-1}$  (8 months). The final two absorption lines listed were listed as usable in analysis of the near-infrared wavelength region by *Ambrico et al.* (2000). Again, it must be emphasized that absorption line analysis must be done for the environment where the measurements are being made, and cannot be universally generalized. These lines, as well as the others picked for the  $830\text{ nm}$

region from *Ambrico et al. (2000)* were not chosen for my measurements because they were determined to be either too weak or too strong for the Bozeman atmosphere.

One limitation of the custom MATLAB OD analysis is that it assumes uniform, constant water vapor distribution throughout the entire range being studied, which is not true and will cause the optical depths to be larger than they would be in reality. Therefore, I wanted to check these numbers with a more realistic simulator, namely HiTRAN-PC. I performed vertical (slant path 90 degrees from horizontal) simulations using the monthly average weather station data for  $T$ ,  $P$ , and  $p_{H_2O}$  as ground-level initial values. The simulation included 10 atmospheric layers of 200  $m$  height each starting from 1.524  $km$  (the GPS-measured altitude of the DIAL instrument) and ending at 3.524  $km$ . The atmospheric model used was either the Arctic winter, U.S. Standard, or Mid-latitude summer model, depending on the time of year being simulated. While using these models corrected the problem of the water vapor being constant throughout the range of measurement, they were still not exactly correct for Bozeman, tending to be too wet in the winter months and too dry in the summer months.

The HiTRAN-PC simulation showed remarkable similarity to the MATLAB analysis, and basically confirmed the results that one absorption line had the optimal line strength throughout most of the year: 12074.5689  $cm^{-1}$ . OD values for both analyses are shown in Table 4.2.

| Month       | Jan.        | Feb.        | Mar.  | Apr. | May  | June        |
|-------------|-------------|-------------|-------|------|------|-------------|
| OD (MATLAB) | 0.93        | 0.71        | 0.96  | 1.38 | 1.56 | $\geq 2.00$ |
| (HiTRAN-PC) | 0.94        | 0.93        | 0.95  | 1.00 | 1.03 | 1.16        |
| Month       | July        | Aug.        | Sept. | Oct. | Nov. | Dec.        |
| OD (MATLAB) | $\geq 2.00$ | $\geq 2.00$ | 1.64  | 1.58 | 1.14 | 0.87        |
| (HiTRAN-PC) | 1.17        | 1.10        | 1.03  | 1.02 | 0.98 | 0.94        |

Table 4.2: Optical Depth values for the water vapor absorption line centered at 12074.5689  $cm^{-1}$  using a custom MATLAB analysis and HiTRAN-PC simulation.

### Nearby Absorption Features

The final criterion for selecting a suitable water vapor absorption line is to ensure that the absorption line is adequately isolated from other absorption features of water vapor or other gasses. Figure 4.8 produced by HiTRAN-PC shows all absorption lines in the  $12059.8167\text{--}12086.0527\text{ cm}^{-1}$  ( $829.2\text{--}827.4\text{ nm}$ ) range, where the best target water vapor lines reside according to the previous temperature sensitivity and OD analysis. All absorption features in this region are due to water vapor. It is evident that several of the candidate water vapor absorption lines listed in the previous section are isolated from and do not overlap with other absorption lines. It is interesting to note that the absorption line at  $12062.4098\text{ cm}^{-1}$  ( $829.022\text{ nm}$ ), used for the horizontal tuning experiments described in Chapter 3 is actually unsuitable for DIAL measurements because it overlaps with two weaker absorption lines that are not sufficiently temperature insensitive. As a DIAL pulse propagates upwards through the atmosphere, the absorption cross sections of these weaker absorption lines would change quickly with temperature, rendering a DIAL measurement on this line useless even though it fits the other two line selection criteria quite well. It is, however, adequate for the horizontal tuning experiments where the temperature and pressure can be assumed to be nearly constant throughout the entire horizontal pathlength, and where the entire absorption feature is scanned across.

### Line Selection

The water vapor absorption line at  $12074.5689\text{ cm}^{-1}$  ( $828.187\text{ nm}$ ) was ultimately selected for use in the MSU water vapor DIAL. It meets the temperature sensitivity requirements, has a line strength that gives nearly optimal optical depth during most months of the year in Bozeman, Montana, and is sufficiently isolated from other

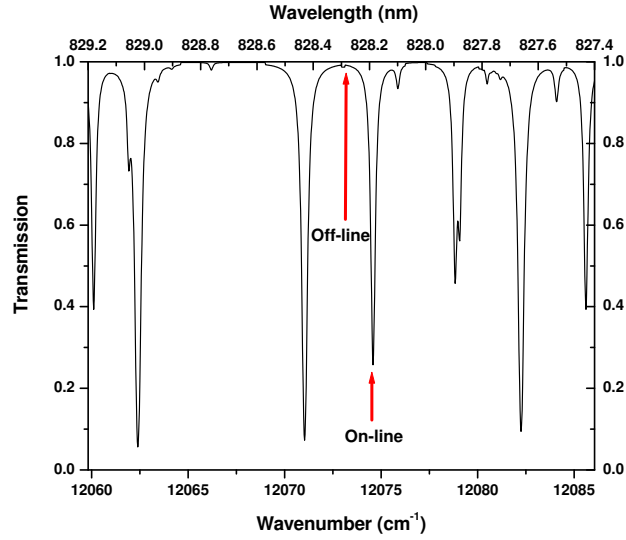


Figure 4.8: A HiTRAN-PC plot at default values of  $1 \text{ atm}$  and  $296 \text{ K}$  across a  $1.5 \text{ km}$  horizontal path length, showing all absorption lines between  $12059.8167 \text{ cm}^{-1}$  and  $12086.0527 \text{ cm}^{-1}$  ( $829.2\text{-}827.4 \text{ nm}$ ). The final on- and off-line wavelengths selected for the water vapor DIAL are indicated.

nearby absorption features. The off-line wavelength was chosen to be  $12073.1099 \text{ cm}^{-1}$  ( $828.287 \text{ nm}$ ) to minimize interference with other absorption features, in particular the absorption line located at  $12075.8654 \text{ cm}^{-1}$  ( $828.098 \text{ nm}$ ). Figure 4.8 indicates the final on-line and off-line wavelengths.

## CHAPTER 5

## DIAL SYSTEM AND EXPERIMENT

Introduction

After it was shown through the horizontal experiments that the ECDL and TA transmitter system would be able to successfully tune across a number of different water vapor absorption features, and taking into account the lessons learned from these experiments, a vertical DIAL system was ready to be designed and built. Since only the transmitter was being tested and hard targets were used for scattering in the horizontal experiments, many of the design inefficiencies could be ignored. This was not the case with a vertical DIAL system. The scattering cross section for atmosphere, especially in a clean-air environment such as Bozeman where aerosols are relatively minimal, is much smaller than that for a hard target. Thus, careful attention had to be paid to the DIAL design to ensure that the maximum number of photons could be transmitted and then counted. Several components used in the horizontal experiments were changed or upgraded. This chapter describes the design considerations that drove the selection of components and subsequent design of the DIAL system. The system is described in detail, along with its characterization and testing. The experimental results of the final DIAL system are shown.

Design

The layout for the DIAL experiment followed the layout of the horizontal tuning

system closely, with several key improvements. Increasing a lidar's transmit power is the quickest way to obtain better signal-to-noise ratio (SNR), so a second tapered amplifier was added to the DIAL. The second way to greatly improve SNR is to decrease background radiation, or in the DIAL case, obtain a narrow-band filter with a very small bandwidth to block as much light outside the laser line as possible. For compact, low-power systems, increasing the average energy output of the laser transmission by using high laser repetition rates increases the SNR. This was accomplished by using a much faster MCS card in the receiver, allowing for higher repetition rates. A fast, stable tuning system that would tune the laser between the on- and off-line wavelengths and hold it stable at the wavelength for the duration of the measurement was developed for the DIAL. This tuning system, along with improvements in the operational and analysis software, allowed the DIAL to become a mostly autonomous instrument, a radical improvement over the horizontal tuning system. These improvements are described in detail later in this section.

The original DIAL design called for placing all transmitter optics, including the laser and amplifiers, on the horizontal surface of a  $2' \times 4'$  optical breadboard to keep the instrument footprint to a minimum. The laser beam would then be sent to a vertical breadboard for transmission into the atmosphere. Placing all of the receiver optics on the opposite side of this vertical breadboard then would allow for isolation and separation of the receiver, especially the APD, from transmitted laser light, greatly reducing background signal in the final data sets. This design would also easily facilitate a bistatic lidar approach, where the receiver field of view (FOV) and transmit beam are not co-located when they leave the system. The limited space of the  $2' \times 4'$  optical breadboard made the optical layout challenging because not only did all of the parts need to fit, but space also had to be factored in to account for the many adjustments and repairs that would be done to the system over time, which,

after all, is still is a prototype.

The first major deviation from the design plan occurred when it was discovered that vertical breadboards with holes drilled and tapped on both surfaces were no longer available for purchase in the size that was needed ( $1' \times 3'$ ). The final transmit optics and receiver optics would have to be overlapped. This design change also made a bistatic approach more difficult, as the transmit beam would have to be directed around the telescope.

Multiple discussions were had about the advantages of a bistatic DIAL system versus a coaxial system, where the transmit beam is sent through the receiver telescope. The advantage of the co-axial system is that in low-power lidar systems where the FOV is very tight to limit background radiation from reaching the detector, the transmit beam and receiver FOV will always be in alignment. Vibrations in the system should affect both the transmit and receive beams identically, and using the telescope to expand and transmit the laser beam ensures that the beam is within the receiver FOV. Bistatic systems are much harder to align with such narrow FOV's, and are subsequently harder to keep in alignment through vibrations and thermal variations. Another problem with bistatic lidars is the overlap function must be accurately accounted for, and care must be taken to ensure the system is in overlap at the altitude where data are desired. The major disadvantage to the coaxial system is that there is not an easy, compact, or inexpensive way to avoid the leading edge of the full-power transmit pulse from being back-reflected into the photon-counting detector, temporarily blinding it at best or damaging it at worst. Pockell cells are one solution for isolating the detector from these back-reflections, but that option was not very feasible in a DIAL receiver as compact as the one that was being designed for this work. Another disadvantage to the coaxial approach is that, as explained in chapter 3, the telescope optics are not optimized for near-infrared light, which would

lower the overall system efficiency since a portion of the transmit beam would be lost as it traveled through the telescope on both the transmit and receive transits. The decision between bistatic and coaxial systems comes down to if the initial blinding and resulting afterpulsing in the detector can be removed through post-processing. If that is the case, then the coaxial technique can be used, as is currently done with Micropulse Lidars (MPL's) (*Campbell et al.*, 2002). However, if the afterpulsing effects cannot be effectively and consistently removed, then a bistatic approach must be used, which has also been used with success (*Machol et al.*, 2004).

Simple calculations were performed to determine how accurate the pointing of a bistatic system would need to be to keep the transmit beam in overlap with the receiver FOV as a function of altitude. The results of these calculations are shown in figure 5.1. If a mirror or other optic in the transmit path caused the beam to deviate by just  $200\ \mu\text{rad}$ , for example, the transmit beam would leave overlap with the receiver FOV at around 800 meters. Primarily because of stability concerns about the transmit beam pointing, the decision was made to make the DIAL a coaxial system.

### System Description

To achieve accurate DIAL data with a low-power vertical system, collecting every return photon is important. For this reason, much care was put into the design of the DIAL system, especially the receiver. Optical design software, Zemax, was used to design the receiver optics. Since the APD active area is  $170\ \mu\text{m}$  in diameter, its size dictated the type of fiber optic cable that could feed photons to it, to avoid over-filling the detector area. The fiber that was used was a custom multi-mode  $105\ \mu\text{m}$  core diameter fiber with a numerical aperture (NA) of 0.22. This fiber size and NA made it the field stop of the receiver system, and defined the full FOV

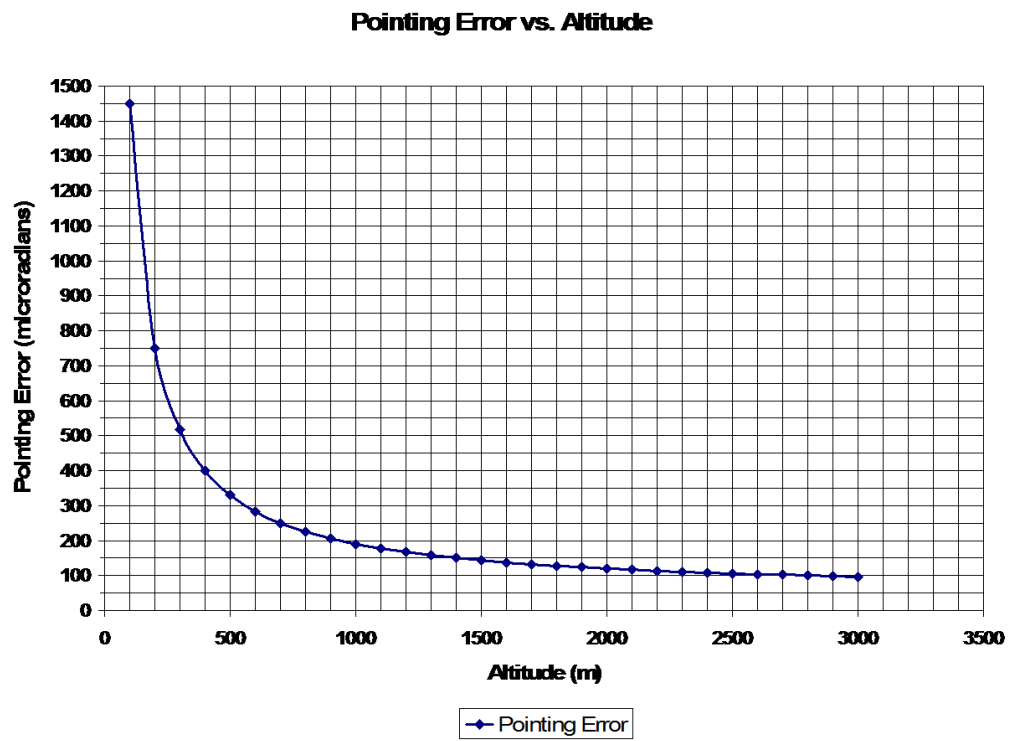


Figure 5.1: A plot of the maximum allowable error in pointing a bistatic laser beam to keep it within the field of view of the detector, as a function of altitude.

of the system to be  $150 \mu\text{rad}$ . The rest of the receiver optics were responsible for taking the photons collected and focused through the telescope, collimating them for passage through the narrowband filter, and focusing them into the fiber to be carried to the APD for detection. Trial-and-error with commercially available optics led to the Zemax design shown in figure 5.2. The vertical line on the left represents the focal plane of the telescope. 8.89 cm (3.5 inches) from there a Newport PAC037 converging lens collimated the beam at a diameter of 9 mm. The collimated space then could contain several optics, including a quarter-wave plate used for allowing return photons, but not transmit photons, to reach the detector, a beamsplitter cube for the future addition of a near-field channel, a PBS where the transmit beam is coaligned with the receiver line, and the narrowband filter. Finally, two Thorlabs lenses (AC127-075-B and AC127-019-B) focused the beam down into the fiber optic cable. The receiver was originally designed to be 33.02 cm (13 inches) from the telescope focal point to the fiber launch.

With the receiver fully designed, the rest of the DIAL could be put together. The ECDL output was circularized by an anamorphic prism pair before passing through two optical isolators to prevent feedback into the laser diode, as in the horizontal tuning experiments. Again a half-wave plate and PBS combination was used to send part of the ECDL beam to a wavemeter for monitoring, and the other part of the beam on to seed the first tapered amplifier. The first TA output was sent through an optical isolator and second half-wave plate and PBS for monitoring. Two mirrors, widely-spaced irises, and a collimating lens were used to seed the second tapered amplifier. The output of this TA was similarly sent through an optical isolator and half-wave plate and PBS. The transmit light was focused and incident on a mirror that turned the beam vertically onto the vertical breadboard. All mirrors and optics were coated for infrared light near 830 nm to minimize scattering and raise system

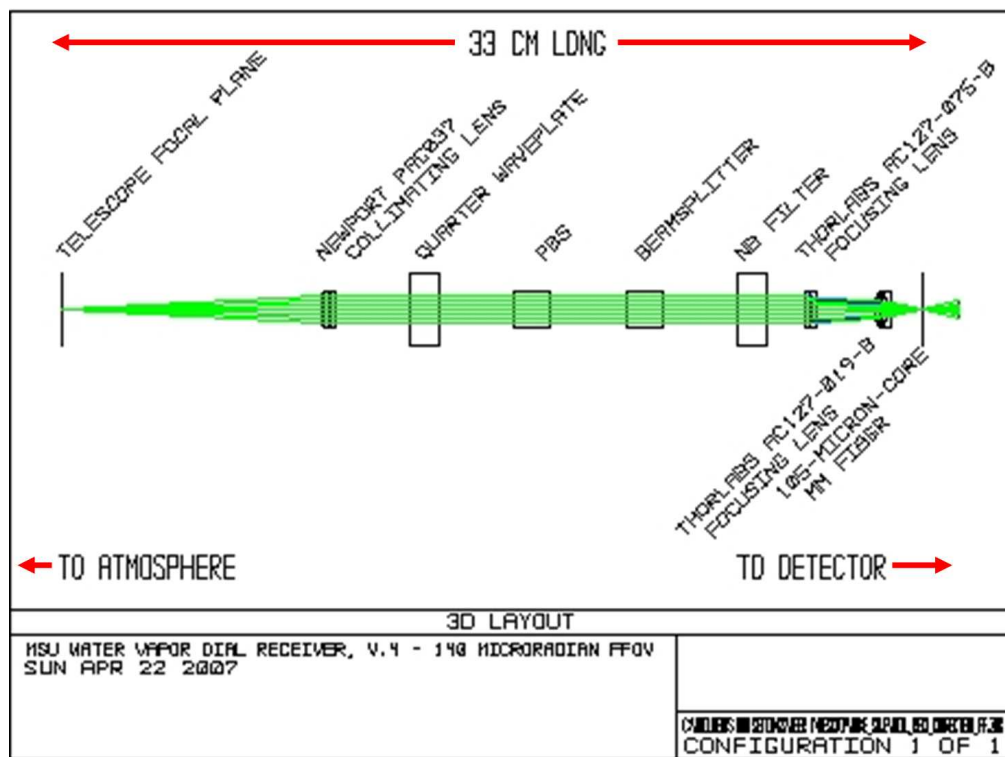


Figure 5.2: A plot produced by Zemax showing the design for the DIAL receiver.

efficiency. A plot of the reflection properties of the mirrors is shown in figure 5.3. The transmit beam was sent through the AOM and then through an iris to block all light except the first-order diffraction pulsed beam. Several flipper mirrors and a fiber launch were included before and after the AOM for use in measuring the spectral purity, as described in the testing section below. The transmit beam was collimated to a diameter of roughly 9 mm after the iris and brought up to a piggy-backed optical breadboard that contained the receiver optics. The transmit beam was brought into the side of the PBS in the receiver line. The transmit light was vertically polarized with respect to the plane of the vertical breadboard, and therefore was reflected out of the PBS towards the telescope in the receiver line. It passed through the quarter-wave plate, causing it to become circularly polarized. After scattering off of a molecule or particle in the atmosphere, the transmit photons would be collected by the telescope, focused, collimated, and sent through the quarter-wave plate now circularly polarized in the opposite direction with respect to the quarter wave plate. This would produce horizontally polarized light with respect to the plane of the vertical breadboard, which would now pass straight through the PBS, through the narrowband filter, and into the fiber. Photons were detected by the APD and counted by a new MCS card. More detailed descriptions of the key components of the DIAL are included below.

The requirements for DIAL measurements with an error due to individual laser properties of  $< 3\%$  are stringent (*Bösenberg, 1998*), yet were still met or exceeded by the final MSU DIAL instrument. These requirements are compared to the current MSU DIAL specifications in Table 5.1.

### Cascaded Tapered Amplifiers

Transmit power is probably the single most critical parameter for lidar perfor-

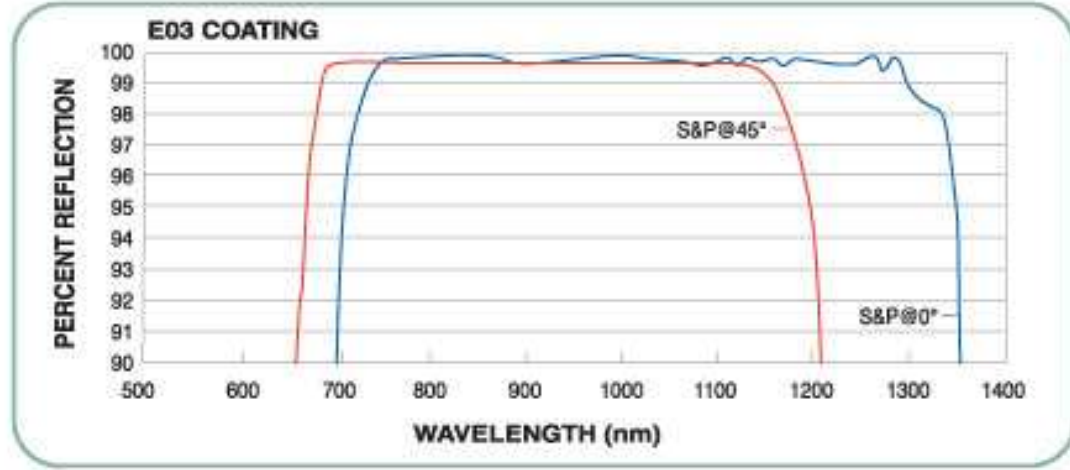


Figure 5.3: A plot of the reflection for the Thorlabs E03 coating, used in all of the mirrors in the DIAL system. Image courtesy of Thorlabs.com.

| Parameter                                  | Measured Value  | Requirement (at 830 nm) |
|--------------------------------------------|-----------------|-------------------------|
| On-/Off-line Wavelength (nm, vacuum)       | 828.187/828.287 |                         |
| Repetition Rate (kHz)                      | 20              |                         |
| Pulse Width ( $\mu s$ )                    | 1.0             |                         |
| Pulse Power ( $\mu J$ )                    | $\sim 0.25$     |                         |
| Linewidth (FWHM; MHz)                      | $< 0.300$       | $< 298$                 |
| Frequency Stability (MHz)                  | $\pm 88$        | $\pm 160$               |
| Spectral Purity                            | 0.995           | $> 0.995$               |
| Telescope Diameter (cm)                    | 28              |                         |
| Far-field Full Field of View ( $\mu rad$ ) | 150             |                         |
| Filter Bandwidth (pm)                      | $\sim 250$      |                         |

Table 5.1: Laser transmitter requirements for water-vapor DIAL measurements with an error due to individual laser properties of  $< 3\%$  compared to the Montana State University DIAL transmitter specifications.

mance. In an attempt to increase the transmit power above the  $\sim 120$  mW maximum power of the horizontal lidar system, a second, cascaded tapered amplifier was added to the DIAL, which to my knowledge is the first time cascaded tapered amplifiers have been used in a DIAL system. The ECDL transmit power is too low to fully saturate the TA that it seeds, but this TA can be used to seed and fully saturate a second TA, allowing it to operate at its maximum output power of  $\sim 400$  mW.

The initial transmit optics are very similar to the setup used in the horizontal tuning experiments. The ECDL is used to seed the first tapered amplifier. The alignment procedure was identical to that of the horizontal tuning experiment. Greater care was taken to provide adequate heat sinks for the TA. However, since the output power of the first TA was kept to  $\sim 20$  mW for seeding the second TA, heating was no longer a problem. The first TA was driven with currents around 2 A, and the temperature was held stable at 21.0° Celsius. The second amplifier was a newer model, and was much harder to align because of a narrower gain region, making it more difficult to send the seed beam completely through the gain region. Because of the difficulty with alignment, the second amplifier was placed on the opposite end of the optical breadboard with relation to the seeding amplifier, allowing for close to a meter of path for the laser to travel between amplifiers. This made it possible to use widely-spaced irises and focusing optics to decrease the beam diameter and more accurately aim it through the gain region of the second amplifier. The second amplifier was also placed on a z-axis translation stage to allow for finer adjustments in seeding.

Effort was put into adequately heat-sinking the second amplifier with mixed results. A heat sink that attached to the amplifier while simultaneously allowing it to be attached to the z-axis translation stage could not be found, and should be machined for future experiments. Smaller heat sinks were attached to the amplifier where pos-

sible, but in the end the amplifier had to be cooled by a fan installed into the wall of the enclosure box close to the second amplifier. Before installation of the fan, the TEC on the second amplifier could not cool it quickly enough, causing the entire system to overheat after only about 1 hour of operation. The amplifier would have to be cooled overnight before another data run was attempted. The other problem with overheating is it causes the spectral quality of the transmit beam to degrade. After installation of the fan, the TEC was able to stabilize the amplifier's temperature at the nominal value of 21.0° Celsius without difficulty. The second amplifier could be operated at full power basically indefinitely without overheating. Tests were run for at least 5 hours straight at full power without the TEC current increasing to continue cooling the amplifier. Experimental tests showed that the fan was balanced enough so that it did not vibrate the entire system.

Overall, as will be seen by test results in the forthcoming test section, the cascaded amplifier design gave a much-needed boost in transmit power, up to an average cw power of  $\sim 250$  mW. The increase in output power was again not as high as we had hoped because of the optics that came after the second amplifier, such as another optical isolator, and mirrors and lenses which each scattered some of the transmit beam. The output power was effectively doubled from the horizontal experiments, though.

A picture of the current and temperature controller for the second amplifier (Pilot 3000 PC) is shown in figure 5.4.

### Multi-channel Scalar Card

To increase the allowable repetition rate of the DIAL, the MCS used for the horizontal tuning experiments was replaced by a much simpler and faster single MCS



Figure 5.4: A picture of the Sacher Lasertechnik Pilot driver used to control the cascaded tapered amplifier in the vertical DIAL experiments.

card (ASRC Aerospace AMCS-USB). The MCS card was built into a user-friendly enclosure by Nick Jurich, an electrical engineering undergraduate. The MCS box operated basically the same as the old MCS, except that without a display screen it would operate much faster than the DIAL would be pulsed at, allowing the DIAL repetition rate to be increased from the horizontal tuning limit of 2272 Hz to 20 kHz, increasing the average output power by nearly a factor of 10.

### Narrowband Filter

To increase the SNR of the DIAL, an extremely narrowband (NB) filter was desired for the receiver to block as much background light outside of the laser wavelength as possible from reaching the detector. Barr Associates manufactures high-quality NB filters with bandpasses of 250 pm that are routinely used in lidar work. With such a narrow band pass, though, care has to be taken to center the filter exactly at the desired wavelength. Water vapor absorption line wavelengths measured in vacuum are separated from wavelengths of the same lines in the atmosphere by more than half of this bandwidth, meaning that a filter designed to be centered at the vacuum wavelength of an absorption line would be rendered useless, as the line would be outside of the band pass in the actual atmosphere. This effect is shown in figure 5.5. An accurate method of calculating the wavelength shift due to the index of refraction

of air needs to be used to ensure that the NB filter is designed correctly. One method is to use an equation, Cauchy's theorem, to theoretically calculate index of refraction of air. This equation is given by

$$n_{air} = 1.000287566 + \frac{1.3412 \times 10^{-18}}{\lambda^2} + \frac{3.777 \times 10^{-32}}{\lambda^4}, \quad (5.1)$$

where  $\lambda$  as usual is the laser wavelength (*Born and Wolf*, 1999). This method is only an approximation as it does not take into account changing atmospheric conditions which can radically affect the index of refraction. At  $\lambda = 828.187 \text{ nm}$ , the index of refraction is computed to be 1.00022.

Another, more experimental, method is to use the wavemeter to measure the index of refraction. The ECDL was tuned to the target on-line vacuum wavelength of 828.187 nm, and then the wavemeter was switched off of vacuum mode and into air mode. It will then use ambient temperature and pressure readings to internally calculate the new air wavelength, from which the index of refraction of air can be computed. Using this method, the index of refraction was computed to be 1.0002896.

Because the wavemeter method took into account actual atmospheric conditions it was deemed to be more accurate, and a NB filter was ordered from Barr with a center wavelength of 828.0069 nm. This specification was correct, as the transmission curve for the NB filter shows in figure 5.6. The on- and off-line wavelengths are marked for reference. Note that the transmission for the off-line wavelength is considerably reduced compared to the on-line wavelength, due to the wide spectral separation of the two wavelengths. A full list of specifications for the narrowband filter are given in table 5.2.

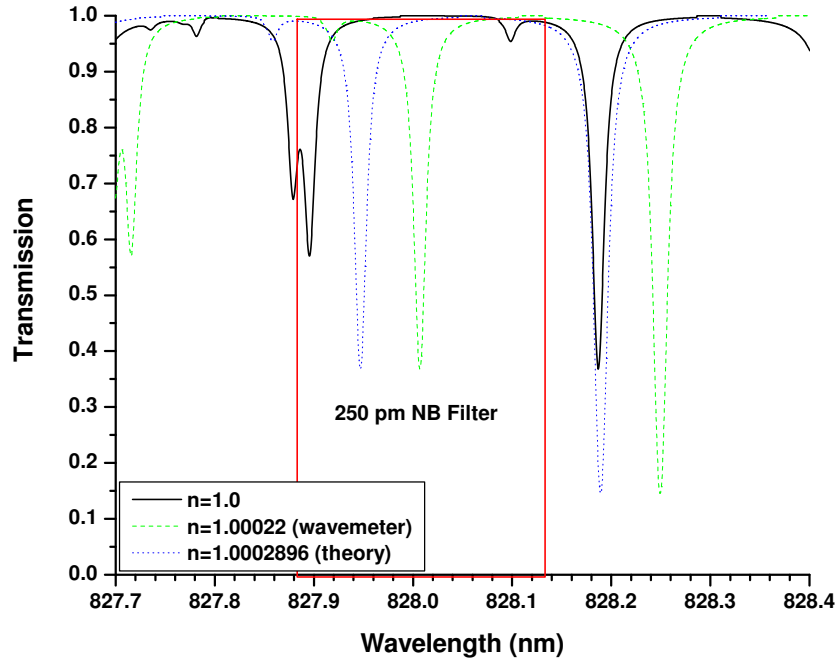


Figure 5.5: A plot of the DIAL’s target water vapor absorption line at 828.187 nm (vacuum wavelength,  $n = 1.0$ ) using HiTRAN-PC. The wavelength shift due to two values of the index of refraction of air is shown. A value of  $n = 1.00022$  was calculated internally by the Burleigh wavemeter using ambient temperature and relative humidity measurements. A value of  $n = 1.0002896$  was calculated using Cauchy’s formula. The red box signifies a hypothetical rectangular band pass region of a 250 pm narrowband filter centered at 828.0069 nm, the line center location using the wavemeter index of refraction.

| Parameter                                    | Value             |
|----------------------------------------------|-------------------|
| Center Wavelength (nm)                       | $828.01 \pm 0.05$ |
| FWHM (nm)                                    | $0.25 \pm 0.05$   |
| Peak Transmission                            | $> 50\%$          |
| Diameter (inches)                            | 1.0               |
| Angle of Incidence ( $^{\circ}\text{C}$ )    | 0                 |
| Operating Temperature ( $^{\circ}\text{C}$ ) | 23.0              |
| Thickness (mm)                               | $< 7.1$           |

Table 5.2: Ordering specifications for the narrowband filter.

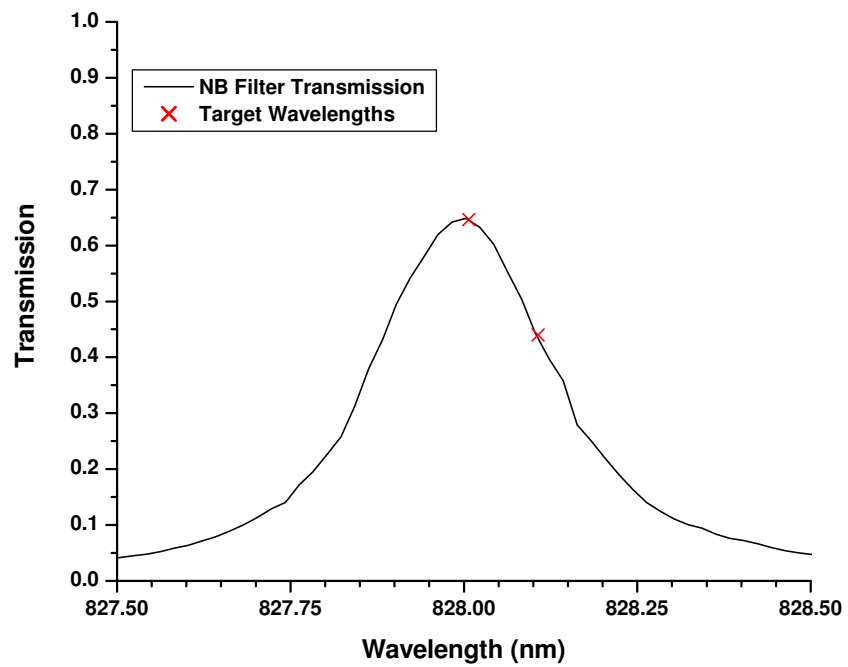


Figure 5.6: A plot showing the transmission curve for the narrowband filter, with the DIAL on-line (828.0069 nm) and off-line (828.1069 nm) labeled. Data for the transmission was provided courtesy of Barr Associates.

### Extended Tuning System

Stable tuning of ECDL's is important for scanning across spectroscopic features, or for quickly changing between frequencies on and off of a spectroscopic feature, as in DIAL. To meet the frequency stability requirements described above, and to ensure that mode hops do not occur in the laser wavelength (or at the very least are accounted for so that they can be removed from the data sets in post-processing), a fast, stable tuning method needed to be developed. Fortunately, a method for extending the continuous tuning range of a ECDL, created by *Repasky et al.*, 2006 for use in oxygen absorption experiments, was able to be modified to provide the fast, stable tuning needed by the DIAL system. It makes use of an electronic feedback loop to suppress mode hops and extend the continuous tuning range of the ECDL. The system and associated tests are also described in detail by *Obland et al.* (accepted for publication, 2007).

A schematic of the tuning setup is shown in figure 5.7. A low-noise current controller was built based on the design of reference *Libbrecht and Hall*, 1993 to serve three purposes. First, it provides a stable dc current to the diode laser. Second, a small RF modulation can be added to the dc current to modulate the wavelength of the ECDL. The current controller converts an RF voltage signal into a modulated current and adds this to the dc set point. Third, a small signal current that is proportional to the voltage applied to the small signal input port can be added to the dc current. The small signal correction current will change the temperature and carrier density of the gain region of the laser diode and thus change the optical path length of the ECDL. In this way, small corrections to the optical path length of the ECDL can be made to synchronize the cavity mode and the frequency of the optical feedback so that mode hops can be suppressed. A function generator is used to provide an RF signal to the current controller to modulate the operating frequency

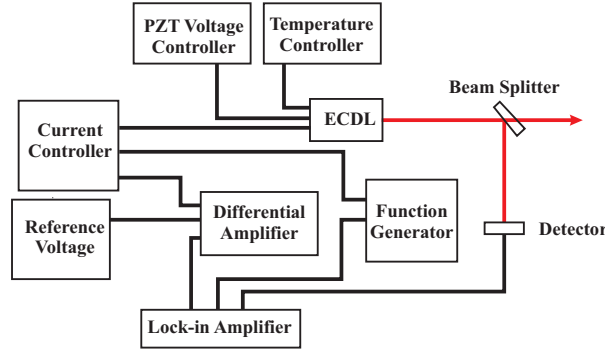


Figure 5.7: A schematic of the extended tuning system for the ECDL.

of the ECDL, which in turn will create a small modulation in the output power of the ECDL as seen by the fast silicon photo-detector. By comparing the phase of the modulated optical power with the phase of the RF signal created by the function generator through the use of a lock-in amplifier, an error signal is created. The error signal created by the lock-in amplifier is sent to a differential amplifier that allows first for the subtraction of a reference voltage and second for amplification of the resulting error signal. Finally, the conditioned error signal is fed into the small signal input port of the current controller to allow corrections to the external cavity length to be made as the laser tunes to synchronize the cavity mode and the frequency of the optical feedback. The result of this electronic feedback scheme is the suppression of mode hops and the extension of the continuous tuning range of the ECDL. The cost of the tuning system, excluding the ECDL and its controllers, is probably less than 10,000 USD and comprised of commercial-off-the-shelf parts. Deploying such a system in the field would require reasonable environmental controls, but is probably less complicated than deploying the laser system in the field.

The optical setup for studying the tuning of the ECDL is shown in figure 5.8. The elliptical output beam of the ECDL is first sent through an anamorphic prism pair to create a nearly circular beam. Next, the beam passes through two Faraday

isolators to prevent back reflections from affecting the performance of the ECDL. After the isolators, a portion of the beam is picked-off using a half wave plate and polarizing beam splitter (PBS) cube. The picked-off beam is next incident on a wedged beam splitter. The light reflected from the wedged beam splitter is sent to a detector used for monitoring the output power of the ECDL, as shown in figure 5.7 for the electronic feedback loop. The light transmitted through the wedged beam splitter is fiber coupled and sent to a Burleigh wavemeter that monitors the operating wavelength of the ECDL. The primary optical beam that passes through the first pick-off is coupled into a commercial solid-state flared amplifier (Sacher Lasertechnik) that provides an amplified collimated circular output beam. The amplified output beam is sent through a Faraday isolator to prevent back reflections from damaging the optical amplifier. A second pick-off using a half wave plate and PBS cube is used to send a portion of the amplified beam to a fiber coupler. The fiber-coupled light can then be used with either a wavemeter or optical spectrum analyzer to monitor the optical spectrum of the amplified beam. The light that passes through the second pick-off is next incident on a wedged beam splitter. The wedged beam splitter reflects about four percent of the laser beam onto a reference power meter that accounts for changes in the power output of the laser system, while the remainder of the amplified beam that passes through the wedged beam splitter is coupled into a sealed gas absorption cell. Light that passes through the gas absorption cell is incident on a second power meter used to measure the transmission through the gas absorption cell.

A second computer-controlled feedback loop to control the ECDL operating wavelength was created as well. The operating wavelength of the ECDL is monitored by the wavemeter and read every 2 seconds by a computer, which then compares the measured wavelength with a user defined desired wavelength. The computer will output a voltage relative to the difference between the actual and desired wavelength

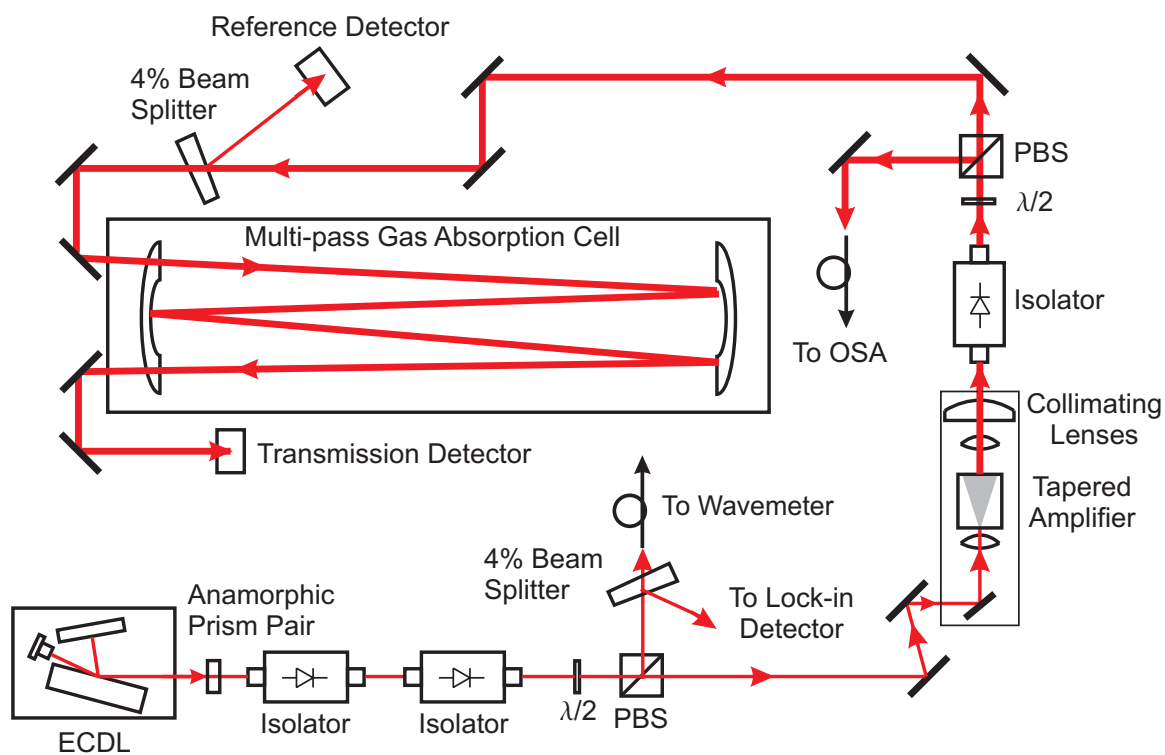


Figure 5.8: A schematic of the gas absorption cell experimental setup. Note that the laser makes 36 passes within the gas absorption cell for a total path length of 19.8 meters.

which is then sent to the piezoelectric transducer used for fine tuning of the operating wavelength of the ECDL. This second computer controlled feedback loop is used to lock the operating wavelength of the ECDL to a desired set point.

### Data Acquisition and Analysis Software

LabVIEW code from the horizontal tuning experiments was modified to create the operational code for the water vapor DIAL, and operated in the following manner. The software (DIAL\_v10.vi, described in appendix D), operating via GPIB connections, initialized the MCS card and all instruments. It then grabbed the date and time for the purposes of file labeling, and for time-stamping every second (20,000 laser pulses) of data. A custom waveform was selected on the arbitrary waveform generator (AWG) that created the desired pulse, a  $1\ \mu\text{s}$  pulsewidth at a repetition rate of 20 kHz. The AWG triggered the APD to begin collecting data but the laser pulse was not activated until  $5\ \mu\text{s}$  later, allowing for a background light measurement to be made. The ECDL PZT voltage was set to zero to initialize it for tuning. The laser was allowed to settle for 5 seconds at the zero PZT voltage and the MCS memory buffer was cleared and readied for data collection. The laser was then tuned to the on-line wavelength and allowed to equilibrate for 5 seconds. The wavemeter feedback loop described in the tuning tests below tuned the laser wavelength until the on-line wavelength was reached. This wavelength and the reference power were measured. The MCS collected data for one second across 500 bins of 50 ns each. A time stamp, the wavelength and reference power, and these bins were recorded to a data file. This procedure of recording wavelength, reference power, and photon counts was repeated as long as desirable at this wavelength, typically 60 seconds, before the laser was tuned to the off-line wavelength and the procedure was repeated there, typically for

90 seconds. The difference in averaging times helped alleviate the lower transmission of the off-line wavelength through the NB filter. This on- and off-line tuning continued as long as was desired, typically for 3-5 hours per data run. The LabVIEW code allowed for real-time display of the wavelength for monitoring tuning, the reference power, and the bin counts.

After the data were taken, MATLAB code was used to analyze it. The analysis code (described in appendix D) scanned the data set and removed data that did not fit within the wavelength stability requirement of  $\pm 160$  MHz of the chosen wavelength. It then averaged the data spatially, binning the counts according to the resolution defined by the pulse width, or 150 meters for 1  $\mu s$  pulses. After spatial averaging, the software normalized the counts with power and subtracted the background measurement from the overall data on a second-by-second basis to increase accuracy. Temporal averaging was typically performed over an hour of data to collect enough signal without allowing the atmosphere to change drastically. This averaging produced difficulties on nights when the atmosphere was changing rapidly, such as on windy nights or when a storm system was entering the area. The averaged and background subtracted counts were then used with absorption cross section values generated from radiosonde temperature and pressure measurements to calculate water vapor profiles using the DIAL equation, equation 2.27.

### Testing

Many tests and diagnostics were run to verify that the DIAL instrument, shown in its complete form in figure 5.9, would be able to meet the stringent requirements for accurate DIAL data, as previously defined.



Figure 5.9: A picture of the DIAL instrument in its operational form inside the roofport room of Cobleigh Hall.

### Noise and Background Signal Levels

Tests were run to determine how well the APD was isolated from background light. Results from these tests are shown in table 5.3. Note that for these tests the telescope receiver was uncovered, so any background light present in the room would have a path to reach the detector. The room lights were kept off. When only the ECDL was on, the APD was counting very near to its stated noise floor of  $\sim 150$  counts per second. Activating the first tapered amplifier slightly increased the number of photons being counted. Activating the second tapered amplifier increased the background level more, even with the AOM inactive and completely blocked. This is an indication of light from the second TA finding a path into the APD independent of the transmit beam. When the AOM was active but still blocked, the background level increased dramatically, indicating either that light being pulsed through the AOM is reaching the APD independent of the transmit beam path, or that reflections off of the beam block were reaching the detector, which would not be a problem in

| Configuration                           | Counts/Second      |
|-----------------------------------------|--------------------|
| APD Dark Count (from manufacturer)      | $\sim 150$         |
| ECDL Only                               | 168.97             |
| ECDL and TA 1                           | 170.77             |
| ECDL, TA 1, TA 2, AOM off and blocked   | 218.87             |
| ECDL, TA 1, TA 2, AOM on and blocked    | 321.62             |
| ECDL, TA 1, TA 2, AOM off and unblocked | 1898.79            |
| Viewing Daylight Sky                    | $2.86 \times 10^6$ |

Table 5.3: Results of testing for background light leakage into the APD.

the actual experiment. Leaving the AOM off but unblocked immediately illustrates the problem of light leaking through the AOM crystal and increasing the background light level. This is support for replacing the AOM and finding a way to pulse the amplifiers directly. Finally, as a test of overall filtering of the receiver, the roofport was opened and the detector was allowed to view the sky during daylight hours. As can be seen, the count rate jumped to almost 3 million counts, indicating that much more work has to be done with filtering before daytime measurements will be possible with this system.

### Beam Shape

A camera (Big Sky Laser TM-745) and software program called BeamView were used to image the output of the ECDL and first amplifier, both seeded and unseeded, to better understand the beam quality of the laser system. The laboratory room lights were shut off during the image captures to avoid saturating the camera. The camera was calibrated via software before and between each measurement. The ECDL was run at the typical current of 37 mA. For an image of the ECDL output, the camera was placed after the anamorphic prism pair, optical isolators, half wave plate, and PBS cube. Neutral density filters were placed in front of the camera to avoid damaging it. The front of the camera lens was located a distance of 4.5 inches after the edge of

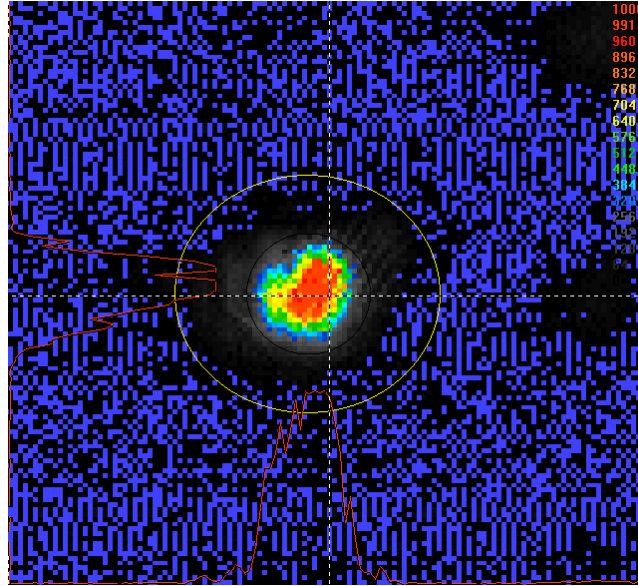


Figure 5.10: A BeamView figure showing the intensity of the ECDL beam after traveling through the anamorphic prism pair, optical isolators, half wave plate, and PBS cube.

the PBS cube. The ECDL output image is shown in figure 5.10, and shows that the beam is relatively circular shortly before it seeds the first amplifier.

The TA was seeded by the ECDL and run at full power of  $\sim 230$  mW with a drive current of 2.997 A. An optical isolator was not used after the tapered amplifier, but again, neutral density filters were placed in front of the camera. For images of the TA output, the front of the camera lens was placed at distances of 5 inches, 10 inches, and 30 inches from the edge of the TA collimating lens. Figure 5.11 shows the resulting images when the TA was both seeded and unseeded. The images show that the TA output is much more circular when seeded by the ECDL, and becomes more circular in shape with distance.

### Spectral Purity

Spectral purity is defined as the fraction of laser power within the laser linewidth

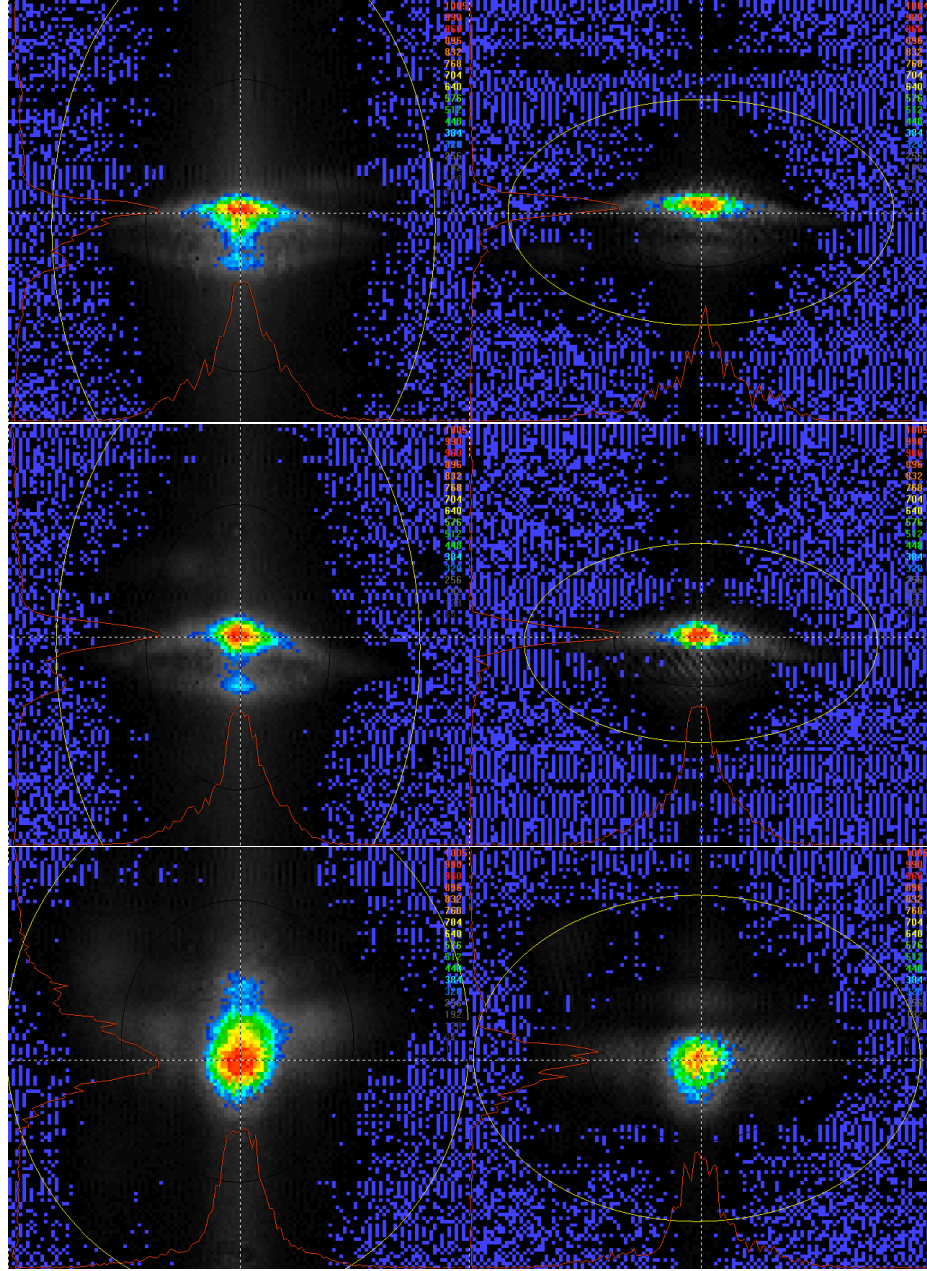


Figure 5.11: These BeamView figures show the tapered amplifier beam shape at 3 different distances from the amplifier, unseeded (left column) and seeded by the ECDL (right column). The top row is at a distance of 5 inches, the middle row is at a distance of 10 inches, and the bottom row is at a distance of 30 inches. The red lines are cross sections of the intensity in two dimensions. The yellow ellipse shows the ellipticity of the beam. Notice that the beam is much more uniform when seeded by the ECDL, and becomes more circular as it propagates.

with respect to the entire output power of the laser. It can also be thought of as basically how much laser power exists outside of the laser linewidth versus how much laser power exists at the desired wavelength. The higher the spectral purity, the less power is in the sidebands of the laser line. It is a critical parameter for accurate DIAL measurements because the assumption is made that the laser is nearly monochromatic, and therefore all of the laser light is absorbed uniformly by an absorption line. If, however, the laser power is spread across a larger spectrum, the laser power will be absorbed differently at each wavelength, and the functional dependence of the laser output power with wavelength must be well known to invert the DIAL equation.

A technique for measuring spectral purity is given by *Wulfmeyer*, 1998. In that paper, the authors describe saturating the air inside of a multi-pass gas absorption cell with water vapor. To measure spectral purity, they then pass the laser beam from their lidar system through this gas cell and measure the amount of power that is transmitted completely through the cell. The idea is that, with the laser wavelength set to line center of the water vapor absorption line, all laser power that is contained within the line width will be totally absorbed by the water vapor. Any power that is not absorbed in the cell must be spectrally located at wavelengths outside of the laser line, giving a measure of spectral purity. An example figure showing a saturated water vapor absorption line at a pressure of 15 mbar plotted with a theoretical 40 MHz wide laser line and a pressure-broadened absorption line is shown in figure 5.12.

One argument about why this approach may not be an entirely accurate method for measuring spectral purity is simply that a saturated water vapor line is not an accurate representation of the shape of water vapor absorption lines in the actual atmosphere. Typically, the absorption line is far from saturated, perhaps only absorbing 70 % of the laser power. Because the line is not saturated, it will also be much thinner. Therefore, laser power that may lie outside of the laser linewidth and still be

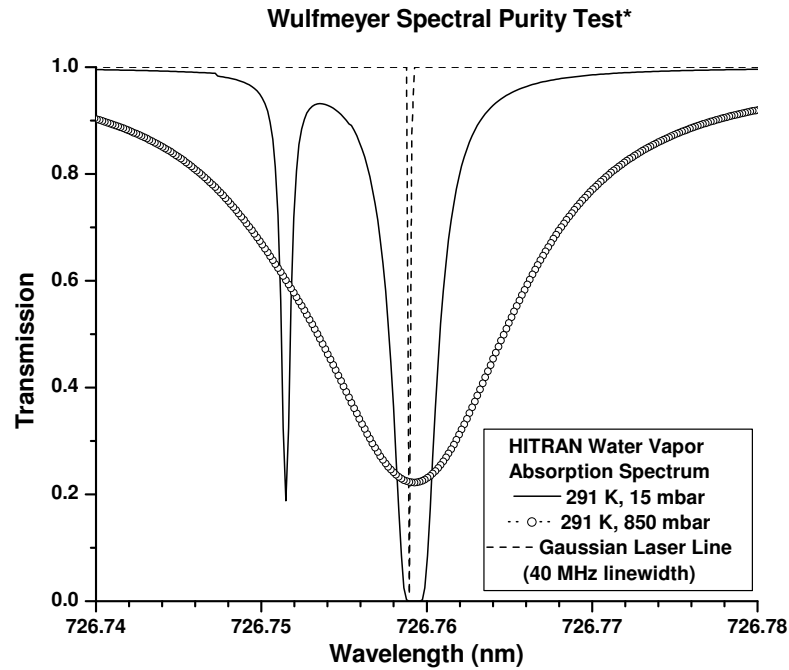


Figure 5.12: A plot of a water vapor absorption line at low pressure (high altitude) or at high pressure, such as in a pressurized multi-pass, gas absorption cell. A hypothetical Gaussian laser line with a 40 MHz linewidth is overplotted for comparison. \*See *Wulfmeyer*, 1998 for a description of using a multi-pass gas absorption cell for making spectral purity measurements.

absorbed by a broadened, saturated water vapor absorption line, may not be absorbed by a much thinner absorption line that would be used to take DIAL measurements, lowering the spectral purity. Perhaps a better technique for measuring spectral purity is to measure the power in the laser linewidth directly from OSA traces, and compare that to the overall power output of the laser beam. This would at least provide a lower limit for the spectral purity of the transmitter. This technique was used to measure the spectral purity of the MSU DIAL.

Initial spectral purity measurements of the DIAL transmitter showed that the system had a spectral purity of 0.872. This value is not surprising since diode lasers and amplifiers based on semiconductor technology tend to have broad spectrums and large amplified spontaneous emission (ASE), hence the use of external cavities to force the diode laser output to be more monochromatic. Adding a narrowband filter to the receiver of the DIAL drastically improves the spectral purity of the system, as only the light that passes through the filter is measured and a large amount of the ASE is blocked. Figure 5.13 shows OSA traces of the power output of the DIAL transmitter both before and after the AOM, on a linear scale with a NB filter in place. Before spectral purity measurements could be made, several questions needed to be answered to ensure that the spectral purity being measured was real and not a relic of the measurement technique itself.

The first question to be answered was whether the spectral purity measurements needed to be made with multi-mode (MM) or single-mode (SM) fibers. Results of measurements made show that the ASE structure is relatively consistent between MM and SM fibers, both before and after the AOM, as seen in figure 5.14. Note that these and subsequent spectral purity measurements are not normalized to each other, so amplitude differences are simply a result of differences in alignment.

The next question to be answered was whether the spectral purity is significantly

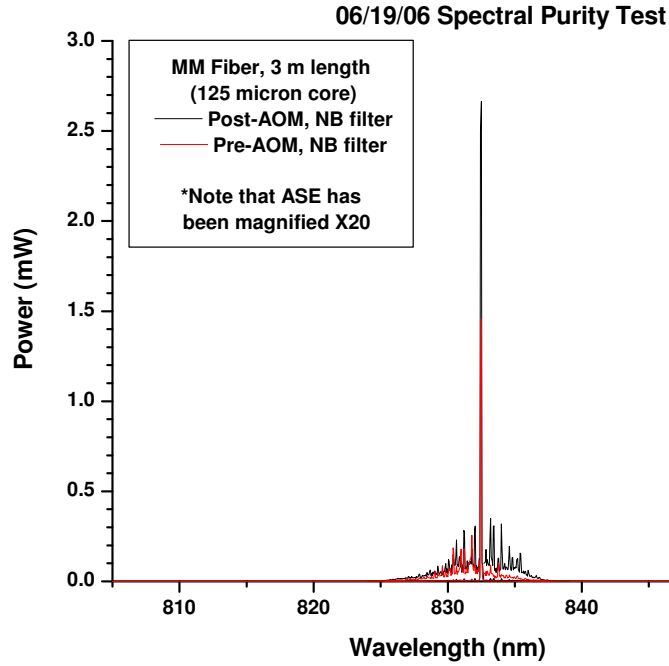


Figure 5.13: A linear plot of the power output of the DIAL transmitter with a narrowband filter in place, measured before and after the AOM through a multi-mode fiber on an OSA.

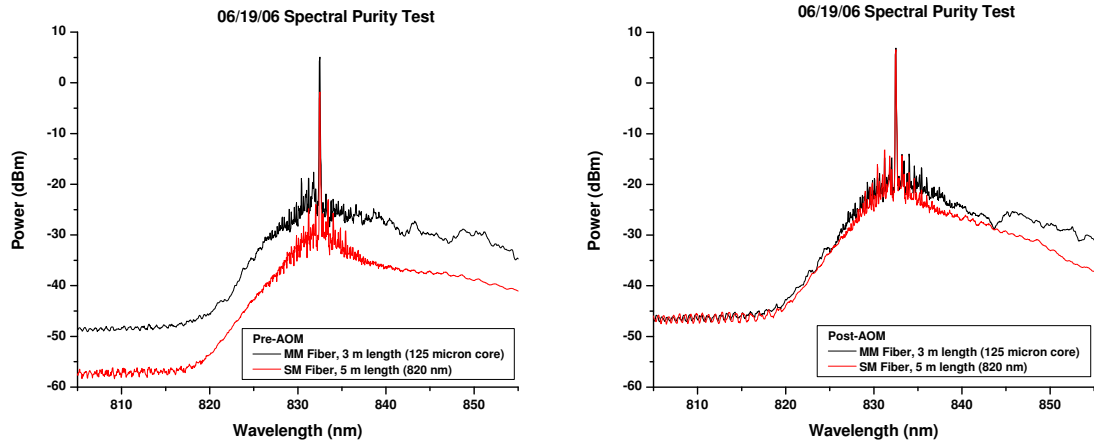


Figure 5.14: These OSA traces show that the ASE structure in the DIAL transmitter output is relatively independent of the type of fiber used to make the measurement, as the structure is similar before (left) and after (right) the AOM for both single-mode and multi-mode fibers.

affected by the presence of the AOM. Figure 5.15 shows the results of OSA traces for both MM and SM fibers, with and without the NB filter, before and after the AOM. The ASE structure is consistent in these comparisons, and shows that the AOM does not seem to have an effect on the spectral purity of the transmit beam.

Finally, the question was posed as to whether the spectral purity measurements depended on the length of fiber optic cable that was carrying the transmit beam to the OSA. The graphs in figure 5.16 show comparisons of MM and SM fibers of varying lengths, before and after the AOM and with and without a NB filter. As before, the ASE structure does not seem to be affected by longer fiber optic cable lengths.

After the method for measuring spectral purity was thoroughly tested and understood, the final OSA measurements were made, and are shown in figure 5.17. As stated before, the spectral purity before use of a narrowband filter is 0.872. With a NB filter in place, the spectral purity of the transmitter improves to  $>0.995$  at the on-line wavelength and  $>0.992$  at the off-line wavelength. Note that the spectral purity for the off-line wavelength does not meet the spectral purity requirements stated in table 5.1, but this should not matter because the off-line wavelength is far removed from any water vapor absorption lines, and therefore the uniform absorption assumption still holds. These tests show that the spectral purity of the DIAL is adequate for accurate water vapor retrievals.

It should be noted that while performing the spectral purity measurements, an interesting correlation between the amount of ASE in the transmit beam and the measured reference power of the beam was observed. It was repeatedly shown by measuring the power modes of the seeded tapered amplifier while simultaneously watching the mode structure of the amplifier output, that the mode of highest power corresponded to the mode with the lowest ASE. Stated another way, the higher the quality of the transmit beam, the higher its power. A possible explanation for this is

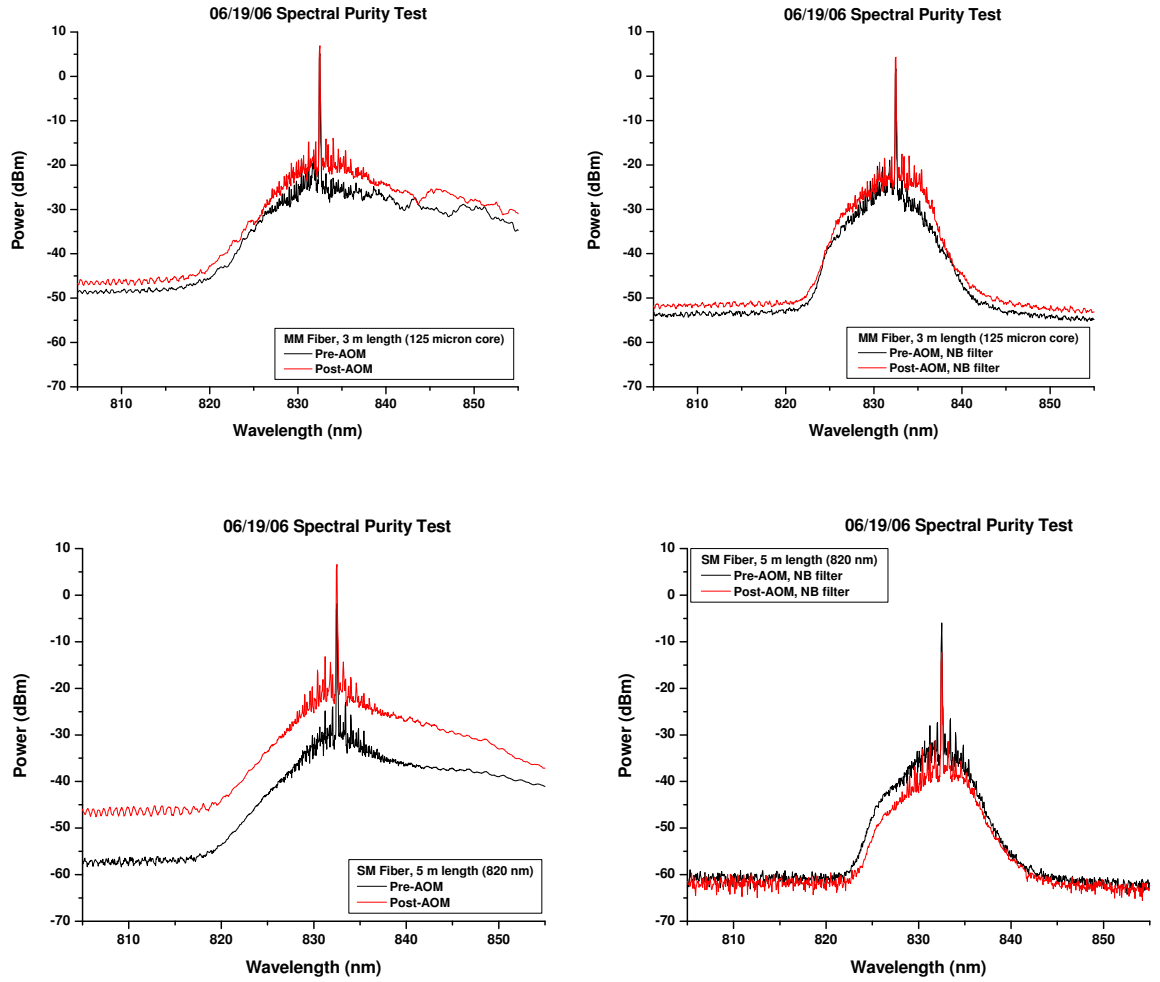


Figure 5.15: These OSA traces show that the ASE structure in the DIAL transmitter output is relatively independent of the presence of the AOM. The structure is similar before and after the AOM for both multi-mode (top row) and single-mode (bottom row) fibers, with (right column) or without (left column) a narrowband filter in place.

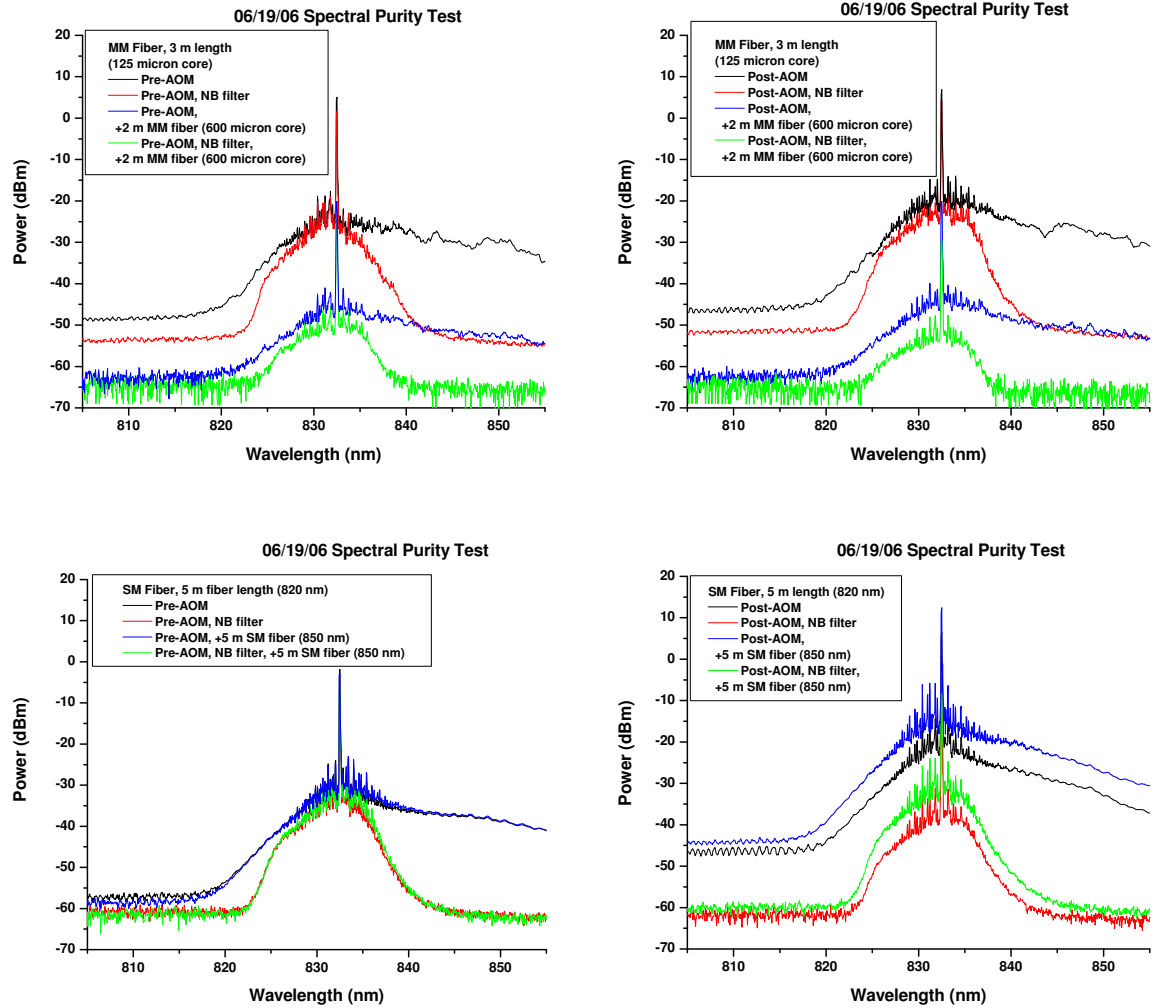


Figure 5.16: These OSA traces show that the ASE structure in the DIAL transmitter output is relatively independent of the length of fiber optic cable being used. The structure is similar before (left column) and after (right column) the AOM for both multi-mode (top row) and single-mode (bottom row) fibers, with and without a narrowband filter in place and for varying fiber lengths.

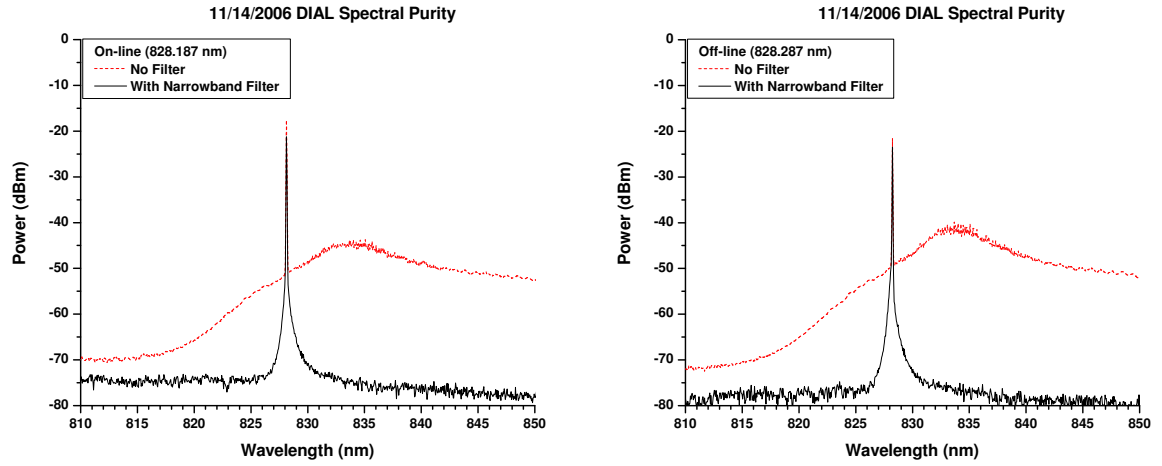


Figure 5.17: OSA traces showing the effect of using a narrow band filter in the receiver of the DIAL. The spectral purity is drastically improved.

that when the amplifiers are correctly seeded the ASE is forced into the primary laser linewidth, increasing the overall power. If the amplifiers are not seeded correctly, power that could be in the laser linewidth is spread to the sidemodes, decreasing the overall measured power. This observation indicated that paying careful attention to correctly seeding the amplifiers before each data run would increase the overall power of the experiment, improving the results.

### P/I Curves

P/I curves were again performed for the ECDL and two amplifiers used for the vertical DIAL experiments, and are shown in figures 5.18 and 5.19. The ECDL was now being driven at a drive current of 40 mA because of the requirements of the extended tuning system. Typically only  $\sim 6$  mW was used to seed the first TA, which was driven at  $\sim 2$  A to seed the second TA with 20-22 mW. The second amplifier driven just below full current,  $\sim 2.8$  A. Higher seed power makes an obvious difference

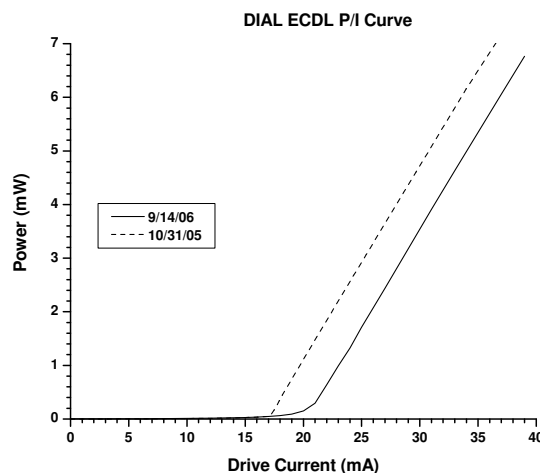


Figure 5.18: The latest P/I curve for the ECDL is plotted against the P/I curve performed almost a year earlier during the horizontal tuning experiments described in Chapter 3. Aging of the diode is evident as it requires more current to reach the same power output.

in the output power of the second TA compared to the first. The second amplifier produced nearly 450 mW output power on a consistent basis.

### Linewidth and Tuning

As in the horizontal tuning tests, optical spectrum analyzer traces of the ECDL and amplifiers were taken, and are shown in figures 5.20 and 5.21. The high quality linewidth and sidemode suppression of the ECDL and TA's is still evident, even though the amplified spontaneous emission of the second amplifier is very evident because it is being run at nearly full drive current and full seed power.

Testing to ensure that the wavelength of the transmit beam after being passed through the AOM was the same as that of the ECDL was performed as in the horizontal tuning experiments: by measuring both wavelengths and forming their ratio for comparison as the ECDL tuned. As expected from previous measurements, the

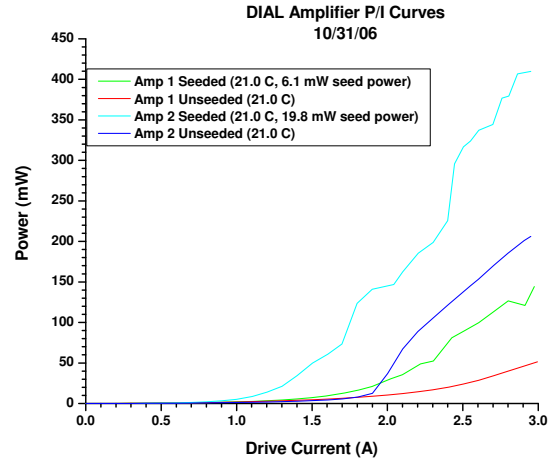


Figure 5.19: P/I curves for the two amplifiers used in the DIAL experiment. Notice the large difference between amplifiers seeded, but not saturated, and seeded at nearly full seed power.

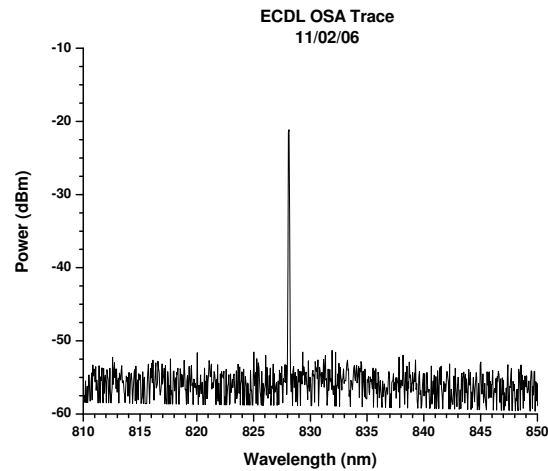


Figure 5.20: An OSA trace of the ECDL output, showing its narrow linewidth and large sidemode suppression.

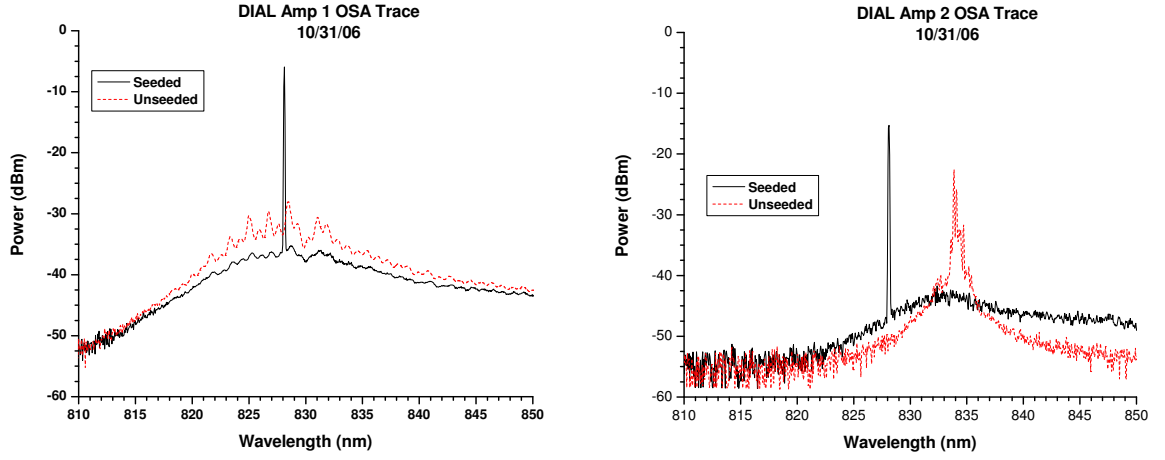


Figure 5.21: OSA traces of the outputs of the DIAL amplifiers. The large increase in amplified spontaneous emission due to higher drive current and seed power for the second amplifier is prominent, but disappears as expected when the amplifier is seeded properly.

results shown in figure 5.22 show that the wavelength output of the DIAL agrees the wavelength being measured from the ECDL to within the uncertainty of the wavemeter,  $\pm 0.1$  pm.

The speed and stability of the extended tuning system that was added to the DIAL was tested in two ways. First, the speed and stability of the tuning system was characterized through direct measurement of the laser wavelength as it locked onto the target on- or off-line wavelength. Second, a differential absorption measurement of water vapor contained in a multi-pass gas absorption cell was used to verify that the system was indeed tuning on and off of a water vapor absorption line. These tests are described in two sections below.

On- and Off-line Tuning Characterization Initial testing and characterization of the tuning of the ECDL were made in the following manner. A computer program was developed that begins by setting the voltage of the PZT used to electronically

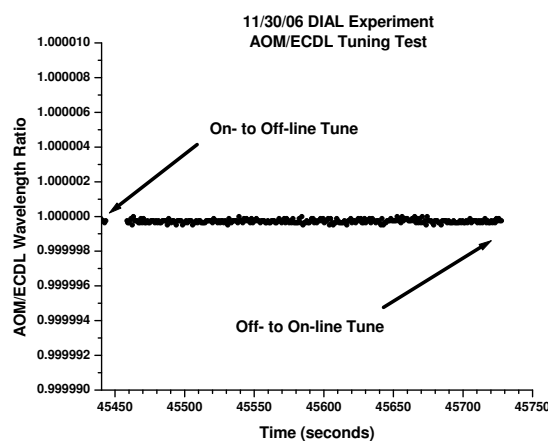


Figure 5.22: A ratio of the laser wavelength measured after the AOM and after the ECDL, showing that the wavelengths agree.

tune the ECDL to zero. The voltage is then changed to a value pre-selected by the user that tunes the ECDL to approximately 828.187 nm ( $12074.5677 \text{ cm}^{-1}$ ), the center wavelength (in vacuum) of a water vapor absorption line. The computer then polls the Burleigh wavemeter every 2 seconds and compares the actual operating wavelength of the ECDL with the desired operating wavelength. If the frequency difference between the actual wavelength and desired wavelength is larger than the resolution of the wavemeter,  $\pm 88 \text{ MHz}$ , a voltage signal is generated and sent to the PZT to tune the ECDL towards the desired operating wavelength and ultimately hold the laser at that wavelength. A plot of the operating wavelength as a function of time is shown in figure 5.23 for different initial starting operating wavelengths of the ECDL. Fine-tuning of the ECDL to the precise wavelength may take a few seconds up to minutes, depending on how close the initial PZT voltage setting, and hence the initial laser wavelength, was to the correct value. By simply checking the voltage settings before starting the experiment, the uncertainty in PZT voltage can easily be reduced to  $\pm 0.01 \text{ V}$ , reducing fine-tuning times to 7-8 seconds between the selected

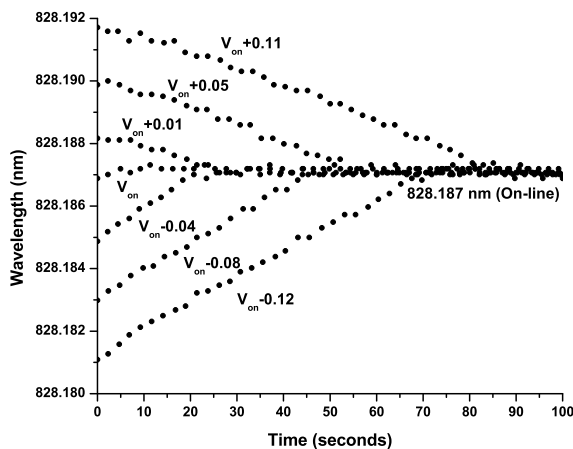


Figure 5.23: A plot of tuning time necessary to lock the laser system to the on-line wavelength, for different initial starting PZT voltage settings, and hence starting wavelengths, of the laser.

wavelengths. This figure indicates that this computer-controlled feedback loop using the Burleigh wavemeter to monitor the operating wavelength and provide a voltage signal to the PZT in the ECDL can robustly reach the desired wavelength.

The ability to tune on- and off-line for differential absorption measurements was studied next. As described in the previous paragraph, the computer program automatically tunes the laser to the desired on-line absorption wavelength of 828.187 nm ( $12074.5677\text{ cm}^{-1}$ ) and uses the computer-controlled feedback mechanism to maintain this wavelength for an amount of time pre-set by the user. The program then tunes the laser to the off-line wavelength, 828.287 nm ( $12073.1099\text{ cm}^{-1}$ , vacuum) and the computer feedback holds this wavelength for another pre-set amount of time. At the end of the off-line measurement period, the PZT voltage is taken to zero before being switched back to the on-line voltage setting to avoid hysteresis in the PZT.

A plot of the operating wavelength as a function of time is shown in figure 5.24, in which the ECDL is quickly tuned about 44 GHz automatically between the on-

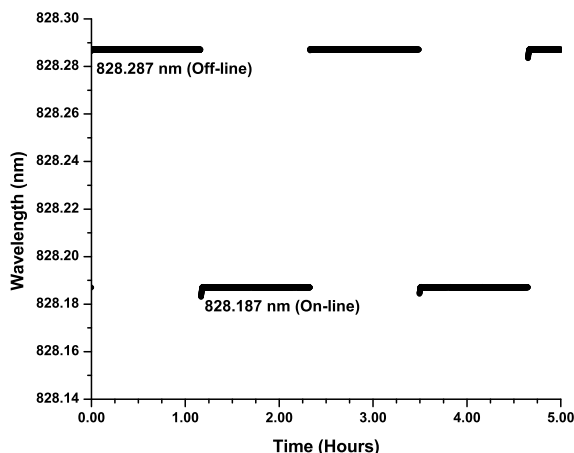


Figure 5.24: A plot showing stable on- and off-line tuning of the laser system at approximately one-hour intervals over a span of five hours.

and off-line wavelengths over a period of 5 hours without mode hopping. Figure 5.25 shows a close up view of the first on-line tuning segment, displaying the ability of the tuning system to tune and hold the laser wavelength to within  $\pm 88$  MHz of the correct on-line wavelength. The frequency stability of  $\pm 88$  MHz ( $\pm 0.00020$  nm) is well within the frequency stability requirement of  $< 200$  MHz ( $< 0.00046$  pm) for accurate water vapor DIAL measurements (Bösenberg, 1998). The ECDL was held at each wavelength for one hour so the long-term stability of the operating wavelength could be determined. This tuning system has been tested for on- and off-line data accumulation times ranging from tens of seconds to over an hour with similar results. Without the extending continuous tuning range due to the electronic feedback loop described above, the ECDL would likely mode hop making the tuning between the on- and off-line difficult and unrepeatable.

Absorption Cell Measurements A multi-pass gas absorption cell was set up to contain a known amount of water vapor so that a differential absorption measurement

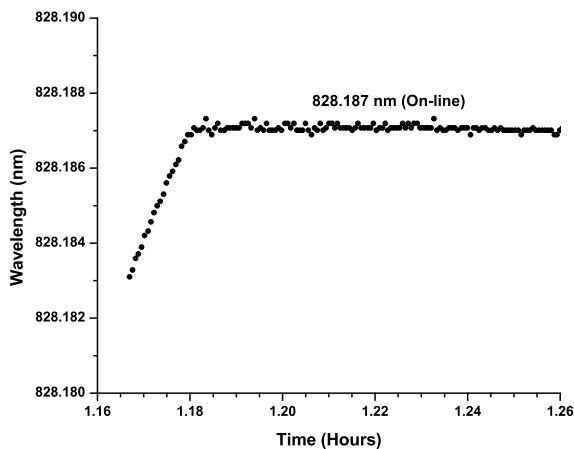


Figure 5.25: An expanded view of the second segment of Fig. 5.24 displaying the computer-controlled feedback loop of the laser system, fine-tuning and holding the laser output to the on-line wavelength, 828.187 nm.

could be made. It was evacuated using a vacuum pump, and then allowed to come into a steady state with a large volume of air above a reservoir containing liquid water. Salt solutions could be used instead of pure water in the reservoir to produce known relative humidities, but were deemed to be unnecessary for these experiments. Fully sealing the container to control the relative humidity was desirable but ultimately too difficult with the available reservoir. Because the reservoir was loosely sealed, the relative humidity obtained in the absorption cell tracked that of the ambient air, but was always higher due to the presence of the volume of water, as illustrated in figure 5.26. The mirrors of the absorption cell were aligned to allow the laser beam to make 36 passes, for a total path length of 19.8 meters. A digital psychrometer (Mannix EM8716) with a stated relative humidity accuracy of  $\pm 3\%$  at  $25^\circ$  Celsius and temperature accuracy of  $\pm 0.6^\circ$  Celsius was placed inside the absorption cell to make an *in situ* measurement of the relative humidity and temperature. Care was taken to ensure the psychrometer did not interrupt the laser beam path.

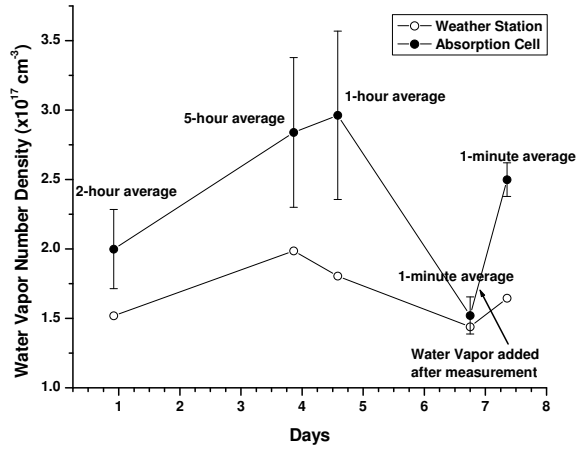


Figure 5.26: A plot of the water vapor number density in the absorption cell compared to the number density in the atmosphere as measured by a weather station on the roof of the building where the absorption cell measurements were performed. Notice that the number density within the absorption cell is always higher than that of the atmosphere due to the presence of the liquid water reservoir connected to the cell. The effect of adding humid air to the absorption cell can be easily seen.

The reference and transmission powers were recorded every two seconds using the computer programs described above, and the normalized transmission power calculated by taking a ratio of the transmission power to the reference power at every data collection point. Figure 5.27 shows the normalized transmission power as a function of time, exactly corresponding to the wavelength tuning shown in figure 5.24. A clear change in transmission between the on-line and off-line normalized transmitted powers is visible. Because the on- and off-line laser beams travel an identical path and are spectrally very close, the assumption is made that all scattering along the path will be identical for both wavelengths, and therefore, the reduction in on-line normalized transmitted power compared to off-line power can be attributed solely to water vapor absorption. To verify that the drop in power is not due to an instrumental effect, tests were run at several nearby and widely spaced pairs of off-line wavelengths, showing no change in normalized transmitted power between two off-line wavelengths. Also,

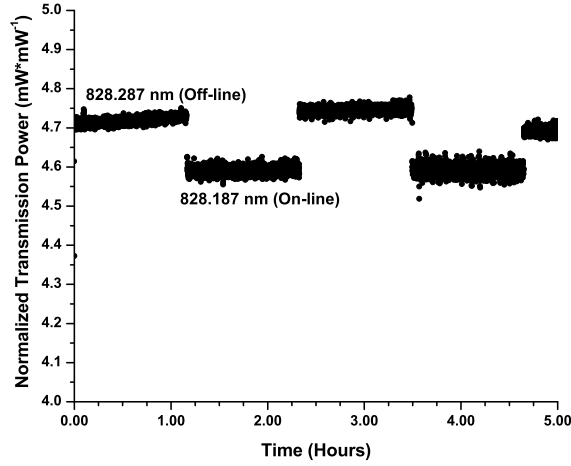


Figure 5.27: A plot of the normalized power transmitted through the 19.8 meter path length of the gas absorption cell. Absorption by water vapor molecules within the cell is responsible for the reduced on-line signal.

since the laser linewidth has been previously measured through beating experiments to be  $\sim 300 \text{ kHz}$  (FWHM), much smaller than the water vapor linewidth of  $\sim 5 \text{ GHz}$  (FWHM), it was tuned across the water vapor line to verify the smooth transition between on- and off-line powers as predicted by HiTRAN-PC.

Using a differential absorption calculation, which is basically a simplified one-way, single-range bin DIAL technique, the number density of water vapor molecules in the absorption cell can be determined by knowing the on- and off-line normalized powers, the absorption cell path length, and the differential absorption cross section of the water vapor absorption line. The number density,  $N [\text{cm}^{-3}]$  is calculated using a one-way, single-range bin DIAL equation,

$$N = \frac{1}{\sigma_{diff} \cdot \Delta R} \ln \left[ \frac{\langle P_{tx,off} / P_{ref,off} \rangle}{\langle P_{tx,on} / P_{ref,on} \rangle} \right], \quad (5.2)$$

where  $\sigma_{diff} = (\sigma_{on} - \sigma_{off}) [\text{cm}^2]$  is the difference between the on- and off-line absorption cross sections due to water vapor,  $\Delta R [\text{m}]$  is the total path length, and

$\langle P_{tx, off(on)} / P_{ref, off(on)} \rangle [mW/mW]$  is the off-line (on-line) normalized transmission power averaged over the measurement time (*Schotland, 1974*). Values from the HiTRAN 2000 database (*Rothman et al., 2003*) were used in custom calculations based on those of *Browell et al., 1991* to determine the absorption profile of the water vapor line and therefore  $\sigma_{on} = 5.685 \times 10^{-23} \text{ cm}^2$  and  $\sigma_{off} = 3.716 \times 10^{-25} \text{ cm}^2$ . Note that  $\sigma_{off}$  is non-zero because the wings of nearby water vapor lines still contribute to absorption at the off-line wavelength. Contributions to the absorption cross sections from the 22 nearest water vapor lines on each side of the absorption line of interest at  $12074.5677 \text{ cm}^{-1}$  were taken into account. The temperature reading for the absorption cell number density calculation was taken from the psychrometer inside the cell, and a pressure measurement with an accuracy of  $\pm 0.5$  mbar was taken by a weather station located on the roof of the building in which the measurements were made. The slight change in pressure between the roof and the laboratory did not make an appreciable difference in the calculated values.

The psychrometer readings averaged over the measurement period were  $48.8 \pm 3.0\%$  for relative humidity and  $21.65 \pm 0.6$  degrees Celsius for temperature. These readings can be used to calculate a partial pressure for water vapor, which can then be converted to a number density (see, for example, (*Kyle, 1991*)). The atmospheric parameters and the calculated partial pressure for water vapor were used with HiTRAN-PC to produce a prediction of the water vapor absorption inside the gas absorption cell. This prediction is compared with the measurements made by the laser system, which have been normalized to the off-line transmission measurement, in figure 5.28. The number density of water vapor molecules in the gas absorption cell determined by the laser system and simplified DIAL technique was  $N = 2.8564 \pm 0.4237 \times 10^{17} \text{ cm}^{-3}$ . The number density measured by the *in situ* psychrometer was  $N = 3.1129 \pm 0.3015 \times 10^{17} \text{ cm}^{-3}$ . The error in the psychrometer measurement of N is due to a slight temperature drift

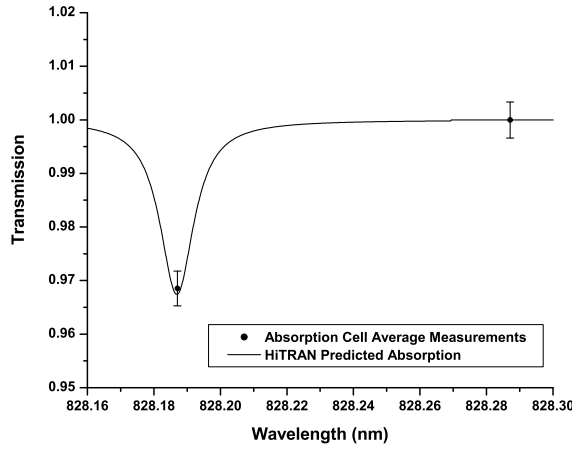


Figure 5.28: A plot of the relative transmission through the gas absorption cell as a function of wavelength. The closed circles represent measurements made by the laser system. The solid line is a theoretical prediction of the absorption by water vapor in the absorption cell using HiTRAN-PC with the *in situ* measurements of temperatures and humidity.

across the measurement period, and the uncertainties in the relative humidity and temperature readings, the latter of which is nonlinear in the conversion from partial pressure to number density. The error in the differential absorption measurement of  $N$  is primarily due to the deviation in the power measurements, which are then enlarged by the natural logarithm in equation 5.2. Both the calculated values for  $N$  and the predicted and measured transmissions agree within their error values.

### Reference Power

Testing the reference power measurement was done in the same manner as for the horizontal tuning experiments. Initially, the DIAL was designed to run similarly to the horizontal tuning experiment, in that the laser would be pulsed for data collection, but would then be switched to cw mode for taking reference power measurements. As will be seen in the data runs section, this method produced a “striping” effect in

the data. A possible solution to this problem was to move the reference power meter to the cw side of the AOM, where it could take a cw measurement of the laser at any time while the laser could remain pulsing. The result of this method is shown in the left graph panel in figure 5.29. It was discovered that there is a relaxing effect present in the AOM in which the power transmitted through the AOM decays over many minutes to a steady value, which probably led to the striping effect in the previous configuration. This effect nullified the technique of measuring the reference power before the AOM, because the transmit power was decreasing through the AOM while the reference power was not. The next, and ultimately final, solution was to leave the reference power meter on the transmit side of the AOM and measure pulse power instead of cw power. Tests were done to show that the power measured by the reference power meter, even while it was pulsing at 20 kHz, was still directly related to the transmit power, as shown by the right graph panel in figure 5.29. Pulsed measurements were noisier when compared to making cw measurements, but were acceptable for the DIAL experiment.

### Data Runs

With the operational tests finished, DIAL data runs commenced on November 14th, 2006. As expected, the coaxial design approach created a large afterpulse in the APD detector, as shown in figure 5.30. The graph shows about 30 minutes of data. The y-axis is the time, starting from the top. Data were taken on 1-second intervals, so every 1-second horizontal row is the number of photons measured by the APD as a function of range. The x-axis is the range in meters. The intensity shows the number of counts in a 50-ns bin. Due to the averaging of the data, the counts represented by the color bar multiplied by a factor of 1000 give the counts per second.

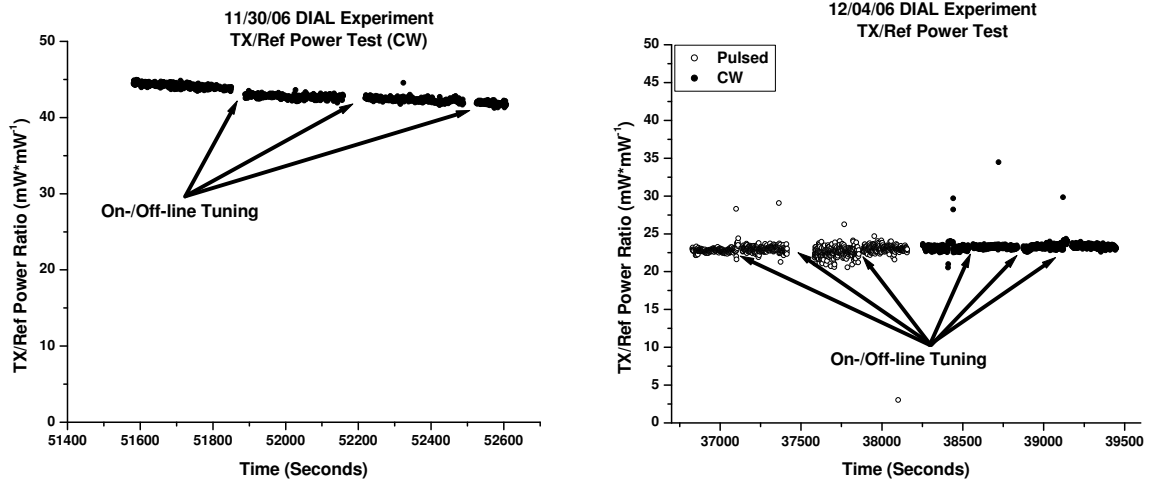


Figure 5.29: Reference power test measurements showing the relaxation effect of the AOM on the left and the difference between pulsed and cw measurements of reference power on the right.

Therefore, the deep red stripe at about 18000 on the color bar, which represents the initial blinding of the APD as the laser fires, is showing a count rate of over 18 million counts per second, which basically means that the APD is saturated. The subsequent vertical stripes located around 750 m, 1500 m, 2250 m, and 2800 m are the ringing of the detector after being blasted by the laser. The horizontal striping is due to the relaxation effect in the AOM after switching the laser to cw mode to measure reference power, as described above. Clearly, there were many data relics that needed to be removed before a small return signal could be extracted from these data.

Because the APD was counting so many photons in every bin, the counts now had to be corrected for missed counts. A correction factor was supplied by the manufacturer and the counts in each bin were multiplied by the factor corresponding to their count rate. The correction factor is shown in figure 5.31. Measuring the reference power by leaving the transmitter in pulse mode, as described in the reference power test section above, eliminated the striping in the time domain. Many attempts

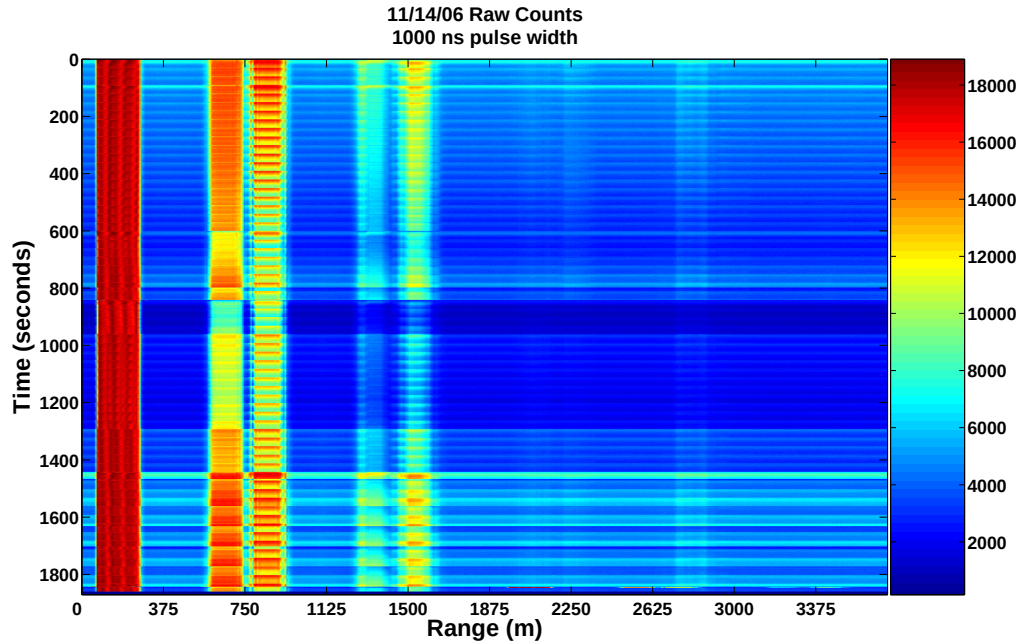


Figure 5.30: An example of initial DIAL data runs, in which the saturation and afterpulse of the APD is apparent, and the striping effect caused by the AOM can be seen.

were made to then remove the afterpulsing effects and background signal from the data. A typical result of such attempts is shown in figure 5.32, where the x-axis is now time of the experiment and the y-axis is range. Negative ranges correspond to the time before the laser fires, which is used to measure the background light level without the laser pulse present. The initial pulse where the APD is saturated cannot be corrected, since counting information is lost in that situation, thus data in those bins were typically set to zero and ignored. To remove the afterpulsing stripes, a time average was taken of the DIAL signal with the roofport hatch open at  $\sim 45^\circ$ , allowing the afterpulse to be measured while ensuring that no atmospheric returns were being collected. This method has been used by other lidars that utilize a coaxial approach (*Campbell et al.*, 2002). It was hoped that the afterpulsing would be uniform enough in time that a time-average could be subtracted from subsequent atmospheric

DIAL data to completely remove the afterpulse stripes. This turned out to not be the case. The afterpulses showed considerable variability and could not be removed consistently. Explanations for this include that the other lidars that use the coaxial technique tend to have higher spatial resolution and higher power. Therefore, the afterpulse is less of a percentage of their data in the spatial domain, and can be more easily ignored if subtraction is not an option. Their designs also use techniques such as blocking the central portion of the secondary telescope mirror, which was not done in the MSU DIAL system to avoid damaging the telescope, and slightly angling optical elements to avoid large back-reflections. After spatially averaging the DIAL data to the typical value of 150 meters, the afterpulse stripes were present in over a quarter of the data bins, meaning they could not be ignored. Also, because of the low power of this DIAL system, the background and afterpulse striping had to be removed to within an accuracy of a few counts per bin, or the level of the expected return signal. The subtraction routine had to be able to remove the highest counts, perhaps around 15,000 counts per bin, to a level of around 15 counts per bin, or 1 in 1000. That level of accuracy was not reliably achievable. For these reasons, it became apparent that the coaxial approach would not work for the DIAL, and the system was redesigned to be bistatic.

The DIAL was redesigned to be bistatic by removing the PBS and quarter-wave plate in the receiver line and no longer bringing the transmit beam up to that level. Instead, the transmit beam was sent around the outside of the telescope, and a 45-degree mirror mount was epoxied to the top of the receiver telescope's secondary mirror housing. Sending the transmit beam off of the back of the secondary telescope mirror allowed the system to be coaligned at ground level, and took some of the alignment uncertainty out of the bistatic approach. Still, it was well known that redesigning for a bistatic lidar was simply trading the coaxial afterpulsing problem

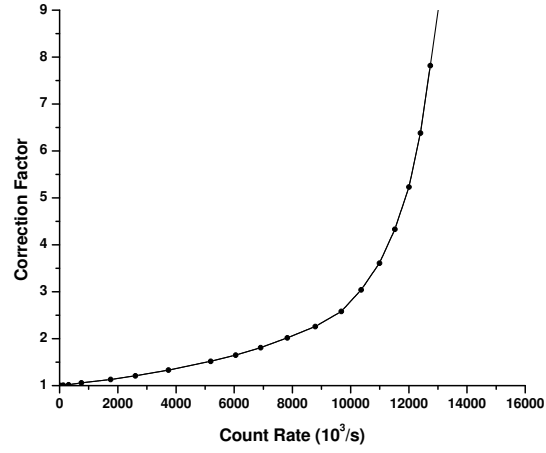


Figure 5.31: The high-count correction factor for the APD detector. Data is courtesy of Perkin-Elmer.

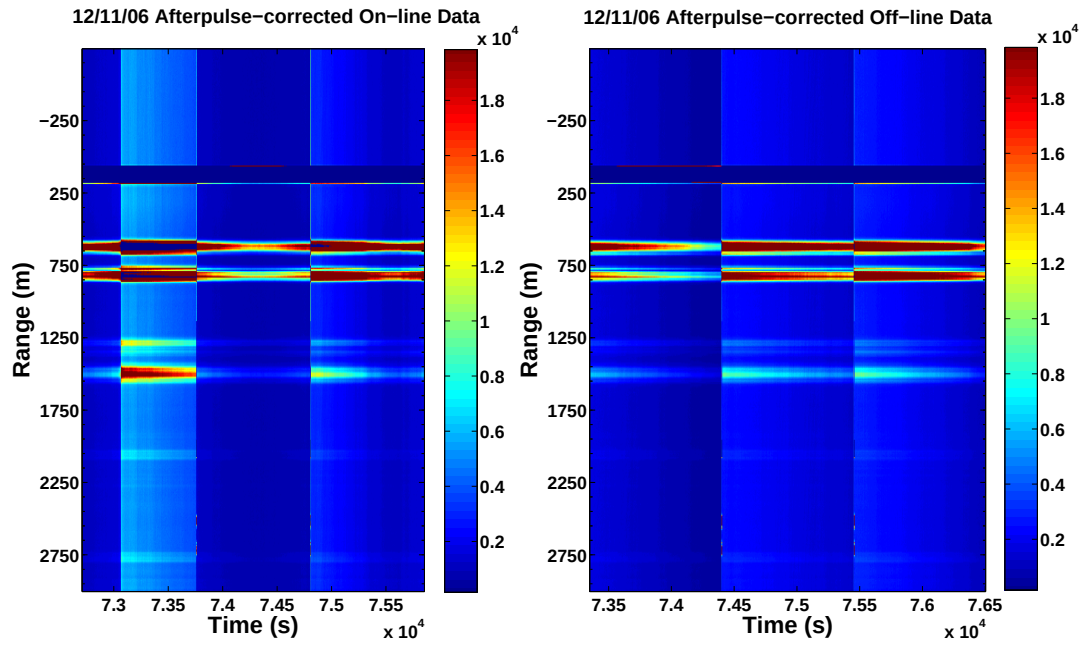


Figure 5.32: Example DIAL data in which the background and afterpulsing effects were attempted to be removed, without success.

for probably an equally difficult alignment problem.

Alignment did turn out to be very difficult. Because the range bins were so large, it was very easy to have the transmit beam misaligned to the point where it was completely out of the receiver FOV within one range bin. The APD still detected a flash from the initial pulse of the laser, but at a much lower level than the coaxial case, and if the transmit beam was not aligned above 150 meters, a return signal would never be seen. Also, the system does not put out enough power to measure an appreciable signal without at least minutes of time averaging. For these reasons, peaking up the alignment of the transmit beam could not easily be done by hand simply by moving the mirrors and watching for increasing return signal in the software. Another method was needed.

Simple calculations showed that the farther out the transmit beam could be reliably aligned with the receiver FOV, the higher in altitude it would remain in alignment before falling out of overlap. Aligning the beam at 1 meter was not sufficient but 30 meters might be. A system was designed where a mirror was placed at roughly 45 degrees over the roofport hatch, and the transmit beam was sent across the roof of the building, hitting the edge about 30 meters away. A visible helium-neon beam was sent backwards through the receiver fiber optic cable to simulate the FOV, and the transmit beam was able to be aligned within the FOV across a 30 meter path length.

This method was successful, and the first bistatic DIAL data were taken on December 21st, 2006, as shown in figure 5.33. The graph again shows time on the y-axis and altitude on the x-axis. The afterpulsing striping disappears in the bistatic approach, and the initial flash of the laser pulse is about 500 times lower, located at around 200 m due to the electronics lag between firing the laser the pulse exiting the system. The initial flash of the laser is so weak that a correction factor for the APD counts was no longer need, as the APD was not anywhere near saturation levels. It

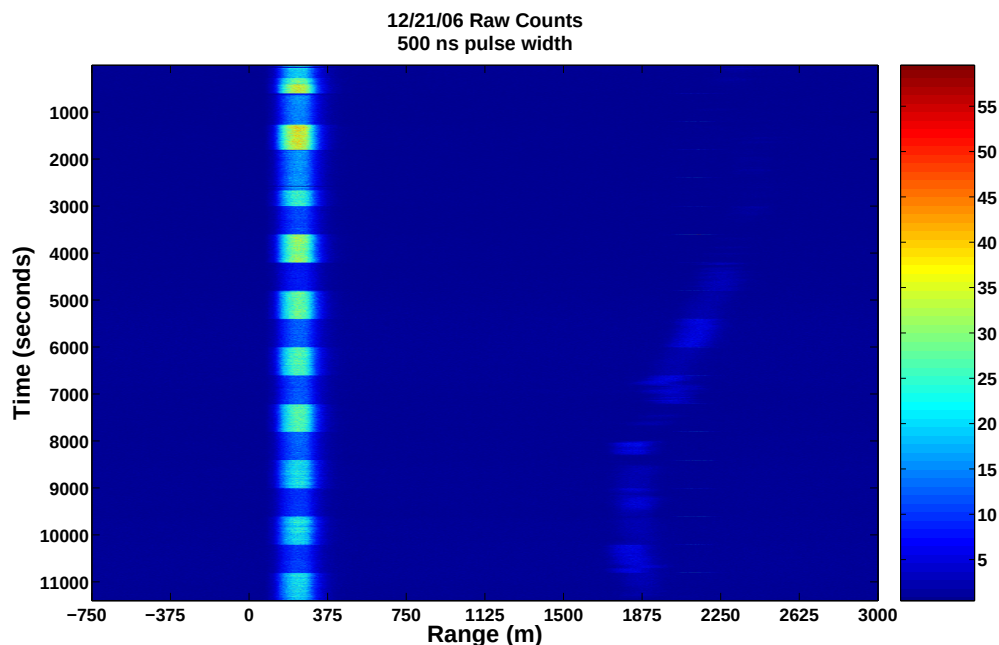


Figure 5.33: Evidence of alignment of the transmit beam with the receiver FOV. The initial laser pulse is 75 meters wide while the flash seen by the detector is over 225 meters wide, indicating return from atmospheric molecules and particles in the near field. Clouds can be seen at about 2.4 km altitude and decrease to about 1.8 km above the ground at the conclusion of the experiment.

is immediately apparent that the system is at least in partial alignment first because the pulse would only produce return off of the transmit optics for a range of 75 m as it exited the system, but the laser flash produces visible returns for a range that is two or three times longer, and second because cloud returns are visible starting at about 2.4 km above the ground and decreasing in altitude as the night went on and a storm system entered the area. At the end of the experiment, the clouds were located at around 1.875 km above the ground and the data run had to be terminated because of rain.

Examples of data containing clouds averaged over time is shown in figure 5.34. In the left graph, the effect of background subtracting can be seen as the bins used for background determination, located below zero altitude, are very near to zero. The

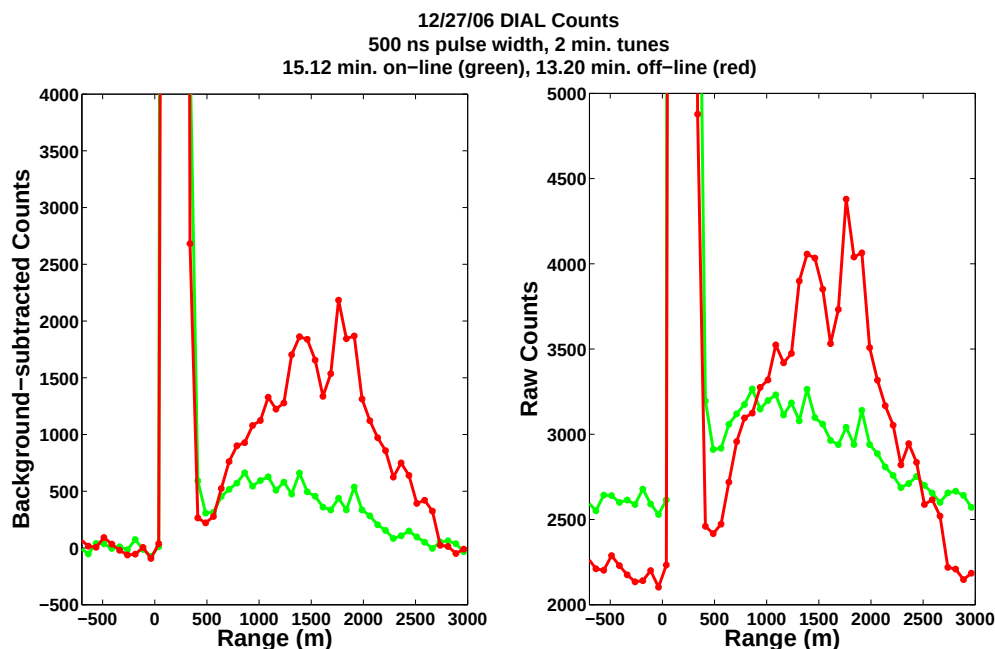


Figure 5.34: Time-averaged raw counts (right) and background-subtracted counts (left) showing the initial laser pulse, atmospheric returns, and cloud returns.

flash of the laser pulse is seen at zero, and lasts much longer than the 75 meters that would be expected if the beam were not scattering off of atmosphere in the near field of the receiver. Clouds are visible from 500 meters in altitude and up. As seen in figure 5.33 as well, the off-line signal is stronger at the clouds because it has not been absorbed by water vapor during its transit from the ground to the cloud and back. The right graph shows the raw counts before background subtraction. The averaged counts such as these are used in the DIAL equation to calculate water vapor density.

With the system in alignment, analysis of the data for producing water vapor profiles could be commenced. To verify that the water vapor DIAL was measuring the accurate amount of water vapor, radiosondes were launched with each DIAL data run, to give an in situ measurement of temperature and relative humidity, which were then converted to water vapor number density. To check the validity of the MSU radiosondes, and to satisfy curiosity, a comparison was performed between an MSU

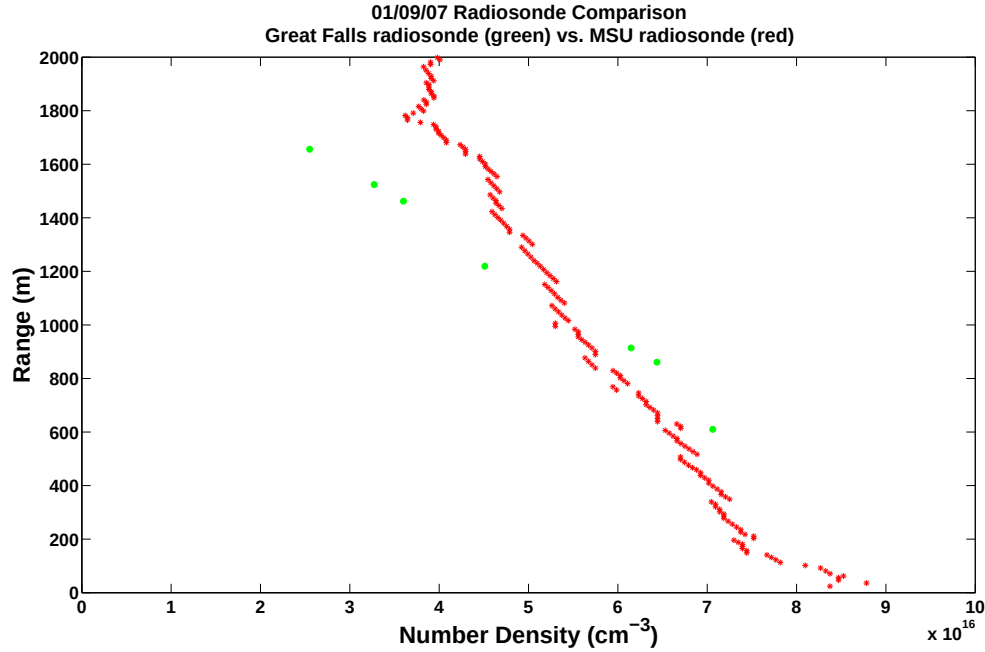


Figure 5.35: A comparison between a radiosonde launched at MSU and one launched in Great Falls around the same time.

radiosonde and a radiosonde launched in Great Falls around the same time. While Bozeman and Great Falls are not located very close to each other, the atmospheric parameters should roughly line up, especially during quiet weather periods. This turned out to be the case, as seen in figure 5.35.

Many nights of data were taken to attempt to produce water vapor profiles. The DIAL was very difficult to keep aligned. The transmit beam would move outside of the receiver FOV easily overnight due to vibrations or thermal changes, meaning the system had to be realigned almost nightly, which it was not built for. The effects of misalignment were very apparent in return signals, as shown in figure 5.36. The system was aligned on January 9th, 2007, and out of alignment on January 18th, 2007. The left graph shows time-averaged on-line counts and the right graph shows time-averaged off-line counts. Notice the steep falloff in the unaligned (green) beam after the initial laser pulse, whereas the aligned (red) beam is considerably longer

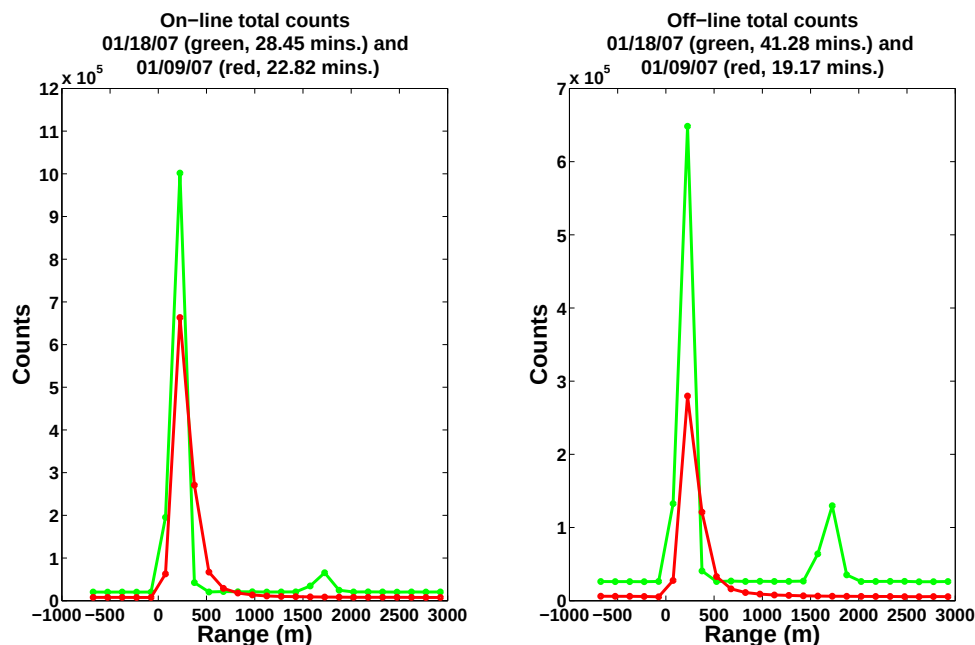


Figure 5.36: A comparison of an aligned (01/09/07) transmit beam and an unaligned (01/18/07) transmit beam. The left graph shows time-averaged on-line counts and the right graph shows time-averaged off-line counts. Notice the steep falloff in the unaligned (green) beam after the initial laser pulse, whereas the aligned (red) beam is considerably longer due to atmospheric returns. The spike above 1500 meters is probably due to multiple scattering of the laser beam within the cloud.

due to atmospheric returns. The spike above 1500 meters is probably due to multiple scattering of the laser beam within the cloud.

Several water vapor profiles were taken while the DIAL was in alignment that agreed reasonably well with the results from a colocated radiosonde. One example is shown in figure 5.37. The data were averaged over about 1 hour with pulse widths of  $1 \mu s$ . Below 500 meters, the data does not agree within the error bars, probably due to a background light leakage into the detector, which has the effect in the DIAL equation of reducing the amount of water vapor. The error bars were produced by a simple differential analysis of the DIAL equation.

This figure shows the ability of the low-power DIAL system to achieve meaningful

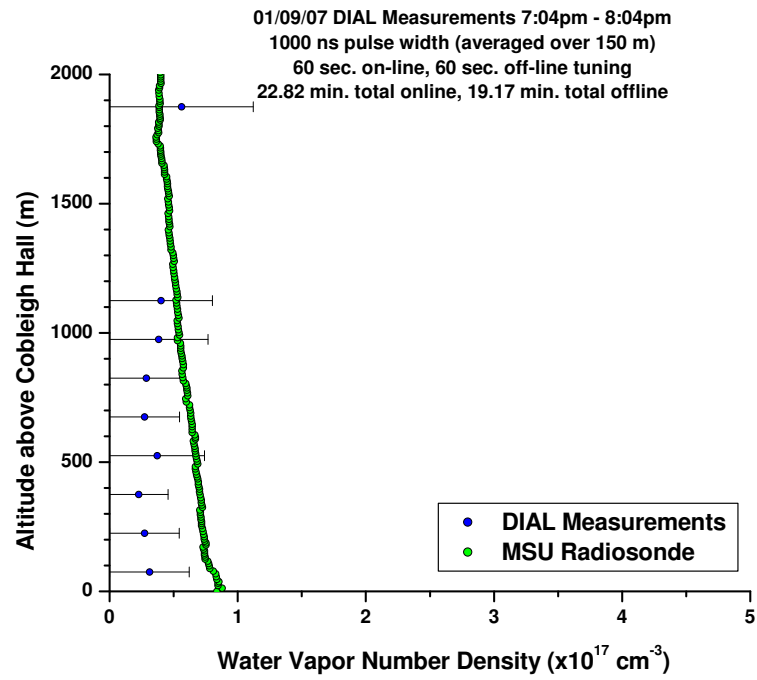


Figure 5.37: A water vapor profile from the DIAL compared to a MSU radiosonde.

water vapor profiles up to about 2 km. While the DIAL returns are not exactly accurate yet, the ability to produce such a close result is a major step towards proving the viability of this system for field deployments, and will only improve with future versions of the instrument.

## CHAPTER 6

## CONCLUSION

A compact, low-power differential absorption lidar (DIAL) using a widely tunable diode laser was built, tested, and used to produce profiles of atmospheric water vapor up to an altitude of 2 km above ground level. The transmitter for the DIAL used a external cavity diode laser (ECDL) that was built through the expertise of the laser source development group at Montana State University (MSU) coupled with a commercial tapered amplifier (TA). The ECDL has the capability of tuning across a 17 nm spectrum near 830 nm, giving it access to numerous water vapor absorption lines.

The tunability of the transmitter was first shown through horizontally pointing lidar experiments in which the laser was tuned across water vapor absorption lines at wavelengths of 829.022 nm, 831.615 nm, and 831.850 nm, in both continuous wave (cw) and pulsed modes. The scans were compared and were in excellent agreement with absorption values given by HiTRAN-PC atmospheric modeling software.

This transmitter was then coupled for the first time in any known DIAL instrument with a second, cascaded TA, and used in a vertically-pointing DIAL. The DIAL used an acousto-optic modulator (AOM) to pulse the cw beam from the transmitter. The receiver made use of a commercial Schmidt-Cassegrain telescope with a diameter of 28 cm, an extremely narrow band (NB) filter with a band pass of  $\sim 250$  pm, and a fiber-coupled, photon counting avalanche photodiode (APD) detector, and had a narrow,  $150\text{-}\mu\text{rad}$  field of view (FOV). Both coaxial and bistatic configurations were attempted, with the bistatic approach producing successful results. The DIAL system was almost completely autonomously controlled using LabVIEW software and a novel

tuning system that quickly tuned the ECDL between the on-line vacuum wavelength of 828.187 nm and off-line vacuum wavelength of 828.287 nm. The tuning mechanism was extensively tested, showing that the laser wavelength could be held stable to within  $\pm 88$  MHz, well within the requirement of  $\pm 160$  MHz for accurate water vapor profiles. The spectral purity was measured to be  $>0.995$ , within allowable tolerances.

Pulses with widths of  $1.0 \mu s$  and energies of  $\sim 0.25 \mu J$ , at a repetition rate of 20 kHz, were used to probe the lower troposphere up to 2 km, resulting in water vapor profiles that were compared to co-located radiosonde measurements. The measurements agreed with the radiosonde measurements to within an order of magnitude, with the discrepancies being explainable and potentially fixable in future DIAL modifications. A number of potential improvements to the system are listed below. Making these changes to the DIAL would create a second-generation instrument capable of accurate nighttime water vapor profiles up to at least 2 km, and potentially capable of daylight profiles.

- It became clear during the DIAL tuning tests and experiments that the PZT within the ECDL housing needs to be replaced. It was noted by monitoring the ECDL wavelength that the PZT no longer seems to be relaxing to its initial position after its external voltage is removed. This effect is definitely growing worse over time and will eventually reach the point where the PZT does not relax at all and the ECDL will not be able to be quickly tuned.
- The commercial tapered amplifiers should be replaced with better versions, probably built at MSU. With custom TA's, like those already being designed and built at MSU, the power output could be increased, heat sinks could be incorporated directly into the TA housing to improve temperature control, and designs could be implemented that would ease the alignment procedures.

- Even if new TA's are not built, more should be done to effectively cool the second tapered amplifier. A heat sink should be machined to pull heat effectively away from the gain region of the amplifier, while still allowing the amplifier to be placed on a translation stage for easier seed alignment. The current fan placement and mounting should probably be improved to ensure against introducing vibration into the system.
- A technique that has been discussed for improving the SNR of the DIAL is to use preferential illumination in which multiple transmit beams are brought into overlap at varying altitudes. In this manner, more laser light could be placed at high altitudes, where it is needed most, smoothing out the dynamic range problem that most lidars face.
- An important step towards a better DIAL system is to find a way to pulse the tapered amplifiers directly and remove the AOM. While this may be difficult unless custom TA's are used, this change immediately removes the problems directly associated with the use of an AOM: a  $> 33\%$  loss in transmit beam power and cw leakage light passing through AOM and raising the background signal level. The drawback to replacing the AOM is that there will probably be less control over the pulse shape, and that may need to be accounted for while processing the data.
- To further reduce the possibility of background light reaching the detector, the DIAL should be redesigned so that the receiver and transmit beam are on opposite sides of the vertical optical breadboard. The receiver optics need to be more isolated from all sources of laser light.
- A complete enclosed box for the receiver box needs to be machined and built.

Even a few background photons passing through the receiver box and reaching the detector is enough to seriously skew the resulting data. If the box was built of metal with fewer seams, it would allow for better isolation. Also, a sturdier receiver box with a top that could be removed would allow easier and quicker access to the receiver optics, which is an improvement over the current need to remove and replace electrical tape over all seams after every receiver adjustment.

- A new technique should be found to reliably align the receiver and transmitter, and the transmit mirror currently epoxied to the top of the secondary telescope mirror housing should probably be permanently attached with a more stable mount.
- One avenue for drastically reducing the amount of background light that reaches the detector is to use a Fabry-Perot etalon as a extremely narrowband filter on the receiver. If the etalon had a band pass that was not much larger than the laser linewidth itself and could be tuned between the on- and off-line wavelengths, this would reduce background light and increase the SNR by a large amount.
- The receiver telescope should be custom coated with anti-reflection coatings for operation near 830 nm. This would increase the efficiency of the receiver and help send more photons to the detector.
- The operational and analysis software codes can always be improved to be made more module for future modifications, more user-friendly, and easier to use so that extensive training is not required to take water vapor profiles.

This DIAL instrument has demonstrated that low-power DIAL instruments using

widely tunable diode laser transmitters, which can be designed at multiple wavelengths, can achieve useful water vapor profiles. The system is robust, can be repaired quickly and relatively easily, compact, and can be made eye-safe, all necessary requirements for an autonomous field or satellite instrument. It is hoped that this DIAL will lead to the development of next-generation, widely tunable DIAL instruments that in the future may be acceptable candidates for use in multi-point lidar networks or satellite arrays to study water vapor flux profiles.

## REFERENCES

- Ambrico, P. F., A. Amodeo, P. di Girolamo, and N. Spinelli, Sensitivity Analysis of Differential Absorption Lidar Measurements in the Mid-Infrared Region, *Appl. Opt.*, *39*, 6847–6865, 2000.
- Aumiler, D., T. Ban, and G. Pichler, High-resolution measurements of the pressure broadening and shift of the rubidium  $5^2S_{1/2}6^2P_{3/2}$  line by argon and helium, *Phys. Rev. A*, *70*, 032,723–+, 2004.
- Battan, L. J., *Fundamentals of Meteorology*, Englewood Cliffs: Prentice-Hall, 1984, 2nd ed., 1984.
- Becker, P. C., N. A. Olsson, and J. R. Simpson, *Erbium-doped fiber amplifiers : fundamentals and technology*, Erbium-doped fiber amplifiers : fundamentals and technology, by P. C. Becker, N. A. Olsson, and J. R. Simpson. San Diego, CD: Academic Press, 1999, xv, 460 p., 1 diskette (3 1/2 in.) Optics and photonics. ISBN 0120845903., 1999.
- Born, M., and E. Wolf (Eds.), *Principles of optics : electromagnetic theory of propagation, interference and diffraction of light*, 1999.
- Bösenberg, J., Ground-Based Differential Absorption Lidar for Water-Vapor and Temperature Profiling: Methodology, *Appl. Opt.*, *37*, 3845–3860, 1998.
- Browell, E. V., S. Ismail, and B. E. Grossmann, Temperature sensitivity of differential absorption lidar measurements of water vapor in the 720-nm region, *Appl. Opt.*, *30*, 1517–1524, 1991.
- Browell, E. V., S. Ismail, and W. B. Grant, Differential absorption lidar (DIAL) measurements from air and space, *Applied Physics B: Lasers and Optics*, *67*, 399–410, 1998.
- Cahen, C., G. Megie, and P. Flamant, Lidar Monitoring of the Water Vapor Cycle in the Troposphere, *Journal of Applied Meteorology*, *21*, 1506–1515, 1982.
- Campbell, J. R., D. L. Hlavka, E. J. Dutton, C. J. Flynn, D. D. Turner, J. D. Spinhirne, V. S. Scott III, and I. H. Hwang, Full-time, eye-safe cloud and aerosol lidar observation at atmospheric radiation measurement program sites: Instruments and data processing, *J. Atmos. Ocean. Technol.*, *19*, 431–442, 2002.
- Churnside, J. H., and J. J. Wilson, Airborne lidar imaging of salmon, *AO*, *43*, 1416–1424, 2004.
- Crutzen, P. J., and F. Arnold, Nitric acid cloud formation in the cold antarctic stratosphere - A major cause for the springtime 'ozone hole', *Nature*, *324*, 651–655, 1986.

- de Labachellerie, M., and G. Passedat, Mode-hop suppression of Littrow grating-tuned lasers, *Appl. Opt.*, *32*, 269–274, 1993.
- Divakarla, M. G., C. D. Barnett, M. D. Goldberg, L. M. McMillin, E. Maddy, W. Wolf, L. Zhou, and X. Liu, Validation of Atmospheric Infrared Sounder temperature and water vapor retrievals with matched radiosonde measurements and forecasts, *Journal of Geophysical Research (Atmospheres)*, *111*, 9–+, 2006.
- Ehret, G., C. Kiemle, W. Renger, and G. Simmet, Airborne remote sensing of tropospheric water vapor with a near-infrared differential absorption lidar system, *Appl. Opt.*, *32*, 4534–4551, 1993.
- Ehret, G., A. Fix, V. Weiss, G. Poberaj, and T. Baumert, Diode-laser-seeded optical parametric oscillator for airborne water vapor DIAL application in the upper troposphere and lower stratosphere, *Applied Physics B: Lasers and Optics*, *67*, 427–431, 1998.
- Fahey, D. W., K. K. Kelly, S. R. Kawa, A. F. Tuck, and M. Loewenstein, Observations of denitrification and dehydration in the winter polar stratospheres, *Nature*, *344*, 321–324, 1990.
- Feltz, W. F., W. L. Smith, H. B. Howell, R. O. Knuteson, H. Woolf, and H. E. Revercomb, Near-Continuous Profiling of Temperature, Moisture, and Atmospheric Stability Using the Atmospheric Emitted Radiance Interferometer (AERI), *Journal of Applied Meteorology*, *42*, 584–597, 2003.
- Gentry, B. M., H. Chen, and S. X. Li, Wind measurements with 355-nm molecular Doppler lidar, *Optics Letters*, *25*, 1231–1233, 2000.
- Goldsmith, J. E. M., F. H. Blair, S. E. Bisson, and D. D. Turner, Turn-Key Raman Lidar for Profiling Atmospheric Water Vapor, Clouds, and Aerosols, *Appl. Opt.*, *37*, 4979–4990, 1998.
- Grant, W. B., Differential absorption and Raman lidar for water vapor profile measurements - A review, *Optical Engineering*, *30*, 40–48, 1991.
- Grund, C. J., and E. W. Eloranta, University of Wisconsin High Spectral Resolution Lidar, *Optical Engineering*, *30*, 6–12, 1991.
- Hair, J. W., L. M. Caldwell, D. A. Krueger, and C.-Y. She, High-Spectral-Resolution Lidar with Iodine-Vapor Filters: Measurement of Atmospheric-State and Aerosol Profiles, *Appl. Opt.*, *40*, 5280–5294, 2001.
- Han, Y., and E. R. Westwater, Remote sensing of tropospheric water vapor and cloud liquid water by integrated ground-based sensors, *J. Atmos. Ocean. Technol.*, *12*, 1050–1059, 1995.

- Harries, J. E., Atmospheric radiation and atmospheric humidity, *Quarterly Journal of the Royal Meteorological Society*, 123, 2173–2186, 1997.
- Intrieri, J. M., M. D. Shupe, T. Uttal, and B. J. McCarty, An annual cycle of Arctic cloud characteristics observed by radar and lidar at SHEBA, *Journal of Geophysical Research (Oceans)*, 107, 5–1, 2002.
- Ismail, S., E. V. Browell, R. A. Ferrare, S. A. Kooi, M. B. Clayton, V. G. Brackett, and P. B. Russell, LASE measurements of aerosol and water vapor profiles during TARFOX, *J. Geophys. Res.*, 105, 9903–9916, 2000.
- Kington, J. A., THE ATMOSPHERIC SCIENCES ENTERING THE TWENTY-FIRST CENTURY, Board on Atmospheric Sciences and Climate Commission on Geosciences, Environment and Resources, National Research Council, USA, National Academy Press, Washington, DC, 1998. No. of pages: xvi+364. Price: #34.95. ISBN 0-309-06415-5 (hardback)., *International Journal of Climatology*, 20, 935–936, 2000.
- Kovalev, V. A., and W. E. Eichinger, *Elastic Lidar: Theory, Practice, and Analysis Methods*, New Jersey, Wiley-Interscience, 615 p., 2004.
- Kyle, T. G., *Atmospheric Transmission, Emission, and Scattering*, Pergamon Press, 1991.
- Libbrecht, K. G., and J. L. Hall, A low-noise high-speed diode laser current controller, *Review of Scientific Instruments*, 64, 2133–2135, 1993.
- Liou, K. N., *An Introduction to Atmospheric Radiation, Second Edition*, San Diego, Elsevier Science, 583 p., 2002.
- Little, L. M., and G. C. Papen, Fiber-Based Lidar for Atmospheric Water-Vapor Measurements, *Appl. Opt.*, 40, 3417–3427, 2001.
- Littman, M. G., and H. J. Metcalf, Spectrally narrow pulsed dye laser without beam expander, *Appl. Opt.*, 17, 2224–2227, 1978.
- Machol, J. L., T. Ayers, K. T. Schwenz, K. W. Koenig, R. M. Hardesty, C. J. Senff, M. A. Krainak, J. B. Abshire, H. E. Bravo, and S. P. Sandberg, Preliminary Measurements with an Automated Compact Differential Absorption Lidar for the Profiling of Water Vapor, *Appl. Opt.*, 43, 3110–3121, 2004.
- McGill, M. J., W. R. Skinner, and T. D. Irgang, Validation of wind profiles measured with incoherent Doppler lidar, *AO*, 36, 1928–1932, 1997.
- McNicholl, P., and H. J. Metcalf, Synchronous cavity mode and feedback wavelength scanning in dye laser oscillators with gratings, *Appl. Opt.*, 24, 2757–2761, 1985.

- Measures, R. M., *Laser remote sensing: Fundamentals and applications*, New York, Wiley-Interscience, 521 p., 1984.
- Meng, L. S., K. S. Repasky, P. A. Roos, and J. L. Carlsten, Widely tunable continuous-wave Raman laser in diatomic hydrogen pumped by an external-cavity diode laser, *Optics Letters*, *25*, 472–474, 2000.
- New Focus Product Guide, 15, 20-39, 2584 Junction Avenue, San Jose, CA 95134-1902, USA (ph. 1-866-683-6287), 2007.
- Nguyen, Q.-V., R. W. Dibble, and T. Day, High-resolution oxygen absorption spectrum obtained with an external-cavity continuously tunable diode laser, *Optics Letters*, *19*, 2134–2136, 1994.
- Obland, M. D., L. S. Meng, K. S. Repasky, J. A. Shaw, and J. L. Carlsten, Progress toward a water-vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source, in *Lidar Remote Sensing for Environmental Monitoring VI. Proceedings of the SPIE, Volume 5887*, edited by U. N. Singh, pp. 205–215, 2005.
- Obland, M. D., K. S. Repasky, J. A. Shaw, and J. L. Carlsten, Preliminary testing of a water-vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source, in *Proceedings of the 23rd International Laser Radar Conference*, edited by C. Nagasawa and N. Sugimoto, pp. 249–252, 2006a.
- Obland, M. D., K. S. Repasky, J. A. Shaw, and J. L. Carlsten, Preliminary testing of a water-vapor differential absorption lidar (DIAL) using a widely tunable amplified diode laser source, in *Proceedings of the 2006 IEEE International Geoscience and Remote Sensing Symposium*, 2006b.
- Obland, M. D., A. R. Nehrir, K. S. Repasky, J. L. Carlsten, and J. A. Shaw, Application of extended tuning range for external cavity diode lasers to water vapor differential absorption measurements, *Optical Engineering*, accepted for publication, 2007.
- Oh, C., C. R. Prasad, V. A. Fromzel, I. H. Hwang, J. A. Reagan, H. Fang, and M. Rubio, Water vapor micropulse differential absorption lidar, in *Proc. SPIE Vol. 3707, p. 177-186, Laser Radar Technology and Applications IV*, Gary W. Kamerman; Christian Werner; Eds., edited by G. W. Kamerman and C. Werner, pp. 177–186, 1999.
- Penchev, S., S. Naboko, V. Naboko, V. Pencheva, T. Donchev, L. Pavlov, and P. Simeonov, DIAL monitoring of atmospheric climate-determining gases employing high-power pulsed laser diodes, in *12th International School on Quantum Electronics: Laser Physics and Applications Edited by P. A. Atanasov, A. A. Serafetinides, and*

- I. N. Kolev, *Proceedings of the SPIE, Volume 5226*, edited by U. N. Singh, pp. 290–294, 2003.
- Poole, L. R., and M. P. McCormick, Polar stratospheric clouds and the Antarctic ozone hole, *J. Geophys. Res.*, *93*, 8423–8430, 1988.
- Prasad, C. R., V. A. Fromzel, J. S. Smucz, I. H. Hwang, and W. E. Hasselbrack, A diode-pumped Cf:LiSAF laser for UAV-based water vapor differential absorption lidar (DIAL), in *Proceedings of the 2000 IEEE International Geoscience and Remote Sensing Symposium*, pp. 1465–1467, 2000.
- Rall, J. A. R., Differential Absorption LIDAR Measurements of Atmospheric Water Vapor Using a Pseudonoise Code Modulated Aluminum Gallium Arsenide Laser., *Ph.D. Thesis*, 1994.
- Rall, J. A. R., and J. B. Abshire, Antarctic Miniature Lidar, in *Proceedings of the 1996 IEEE International Geoscience and Remote Sensing Symposium*, pp. 1538–1540, 1996.
- Rall, J. A. R., J. Kujawski, M. Obland, and M. Ott, Multi spectral lidar (MSL), in *Remote Sensing for Environmental Monitoring, GIS Applications, and Geology V. Edited by Ehlers, Manfred; Michel, Ulrich. Proceedings of the SPIE, Volume 5984*, edited by U. N. Singh, pp. 132–139, 2005.
- Reagan, J. A., T. W. Cooley, and J. A. Shaw, Prospects for an economical, eye-safe water vapor LIDAR, in *Proceedings of the 1993 IEEE International Geoscience and Remote Sensing Symposium*, pp. 872–874, 1993.
- Reagan, J. A., H. Liu, and J. F. McCalmont, Laser diode based new generation lidars, in *Proceedings of the 1996 IEEE International Geoscience and Remote Sensing Symposium*, pp. 1535–1537, 1996.
- Remsberg, E. E., and L. L. Gordley, Analysis of differential absorption lidar from the Space Shuttle, *Appl. Opt.*, *17*, 624–630, 1978.
- Repasky, K. S., and J. L. Carlsten, Simple Method for Measuring Frequency Chirps with a Fabry Perot Interferometer, *Appl. Opt.*, *39*, 5500–5504, 2000.
- Repasky, K. S., P. Roos, L. S. Meng, and J. L. Carlsten, Amplified output of a frequency chirped diode source via injection locking, *Optical Engineering*, *40*, 2505–2509, 2001.
- Repasky, K. S., G. W. Switzer, and J. L. Carlsten, Design and performance of a frequency chirped external cavity diode laser, *Review of Scientific Instruments*, *73*, 3154–3159, 2002.

- Repasky, K. S., J. A. Shaw, J. L. Carlsten, M. D. Obland, L. S. Meng, and D. S. Hoffman, Diode laser transmitter for water vapor DIAL measurements, in *Proceedings of the 2004 IEEE International Geoscience and Remote Sensing Symposium*, vol. 3, pp. 1947–1950, 2004.
- Repasky, K. S., A. R. Nehrir, J. T. Hawthorne, G. W. Switzer, and J. L. Carlsten, Extending the continuous tuning range of an external-cavity diode laser, *Appl. Opt.*, *45*, 9013–9020, 2006.
- Rothman, L. S., A. Barbe, D. C. Benner, L. R. Brown, C. Camy-Peyret, M. R. Carleer, K. Chance, C. Clerbaux, V. Dana, V. M. Devi, A. Fayt, J.-M. Flaud, R. R. Gamache, A. Goldman, D. Jacquemart, K. W. Jucks, W. J. Lafferty, J.-Y. Mandin, S. T. Massie, V. Nemtchinov, D. A. Newnham, A. Perrin, C. P. Rinsland, J. Schroeder, K. M. Smith, M. A. H. Smith, K. Tang, R. A. Toth, J. Vander Auwera, P. Varanasi, and K. Yoshino, The HITRAN molecular spectroscopic database: edition of 2000 including updates through 2001, *Journal of Quantitative Spectroscopy and Radiative Transfer*, *82*, 5–44, 2003.
- Rycroft, M. J., Global environmental change: research pathways for the next decade - by Committee on Global Change Research of the US National Research Council, National Academy Press, 1999, 595 pp. ISBN: 0 309 06420 1, (hb) @\$39.95, *Journal of Atmospheric and Terrestrial Physics*, *62*, 711–712, 2000.
- Sassen, K., The Polarization Lidar Technique for Cloud Research: A Review and Current Assessment., *Bulletin of the American Meteorological Society*, vol. *72*, Issue *12*, pp.1848-1866, *72*, 1848–1866, 1991.
- Schotland, R. M., Some observations of the vertical profile of water vapor by means of a ground based optical radar, in *Proceedings of the Fourth Symposium on Remote Sensing of the Environment*, pp. 273–283, University of Michigan, Ann Arbor, Mich., 1966.
- Schotland, R. M., Errors in the lidar measurement of atmospheric gases by differential absorption, *J. Appl. Meteor.*, *13*, 71–77, 1974.
- Schott, J. R., *Remote Sensing: the image chain approach*, New York, Oxford University Press, 1997, 424 p., 1997.
- Seldomridge, N. L., J. A. Shaw, and K. S. Repasky, Dual-polarization lidar using a liquid crystal variable retarder, *Optical Engineering*, *45*, 106,202, 2006.
- Shaw, J. A., <http://www.coe.montana.edu/ee/weather/>, 2006.
- Shaw, J. A., J. J. Bates, W. L. Eberhard, R. J. Alvarez II, S. P. Sandberg, and L. Larrabee Strow, Atmospheric measurements with unattended FTIR and Lidar,

- in *Technical Digest, Optical Society of America Topical Meeting on Optical Remote Sensing of the Atmosphere*, pp. 77–79, 2001.
- Shaw, J. A., N. L. Seldomridge, D. L. Dunkle, P. W. Nugent, L. H. Spangler, J. J. Bromenshenk, C. B. Henderson, J. H. Churnside, and J. J. Wilson, Polarization lidar measurements of honey bees in flight for locating land mines, *Optics Express*, *13*, 5853–+, 2005.
- Souprayen, C., A. Garnier, A. Hertzog, A. Hauchecorne, and J. Porteneuve, Rayleigh-Mie Doppler wind lidar for atmospheric measurements. I. Instrumental setup, validation, and first climatological results, *AO*, *38*, 2410–2421, 1999.
- Spinhirne, J. D., Micro pulse lidar, *IEEE Transactions on Geoscience and Remote Sensing*, *31*, 48–55, 1993.
- Stelmaszczyk, K., M. dell’Aglia, S. Chudzynski, T. Stacewicz, and L. Wöste, Analytical function for lidar geometrical compression form-factor calculations, *Appl. Opt.*, *44*, 1323–1331, 2005.
- Stephens, G. L., *Remote Sensing of the Lower Atmosphere: an introduction*, New York, Oxford University Press, 544 p., 1994.
- Switzer, G. W., Semiconductor laser transmitter for water vapor lidar on Mars, *Ph.D. Thesis*, 1999.
- Turner, D. D., W. F. Feltz, and R. A. Ferrare, Continuous Water Vapor Profiles from Operational Ground-Based Active and Passive Remote Sensors., *Bulletin of the American Meteorological Society*, vol. *81*, Issue *6*, pp.1301-1318, *81*, 1301–1318, 2000.
- Turner, D. D., R. A. Ferrare, L. A. Heilman Brasseur, W. F. Feltz, and T. P. Tooman, Automated retrievals of water vapor and aerosol profiles from an operational Raman lidar, *J. Atmos. Ocean. Technol.*, *19*, 37–50, 2002.
- Wulfmeyer, V., Ground-Based Differential Absorption Lidar for Water-Vapor and Temperature Profiling: Development and Specifications of a High-Performance Laser Transmitter, *Appl. Opt.*, *37*, 3804–3824, 1998.
- Wulfmeyer, V., and J. Bösenberg, Ground-Based Differential Absorption Lidar for Water-Vapor Profiling: Assessment of Accuracy, Resolution, and Meteorological Applications, *Appl. Opt.*, *37*, 3825–3844, 1998.
- Wulfmeyer, V., and C. Walther, Future Performance of Ground-Based and Airborne Water-Vapor Differential Absorption Lidar. I. Overview and Theory, *Appl. Opt.*, *40*, 5304–5320, 2001.

## APPENDICES

APPENDIX A

PRELIMINARY LIDAR EXPERIMENTS

## Other Lidar Experiments

Besides the experiments directly related to making DIAL measurements of water vapor, and the development that went into creating those experiments, many other projects were undertaken to learn about the intricacies of lidar systems and development, or to advance other technologies. This appendix describes one such project, involving the design, construction, and testing of a fiber optic laser amplifier at NASA Goddard Space Flight Center (GSFC) for use in an Antarctic lidar. The opportunity to go to GSFC and work on this project was funded by the NASA Graduate Student Researchers Program (GSRP). My advisors at GSFC were Dr. Jonathan Rall and Mr. Joe Kujawski. Part of this work was reported by *Rall et al.*, 2005.

### NASA Goddard Space Flight Center (GSFC) Fiber Optic Laser Amplifier

#### Introduction

Polar stratospheric clouds (PSCs) are optically thin clouds that have been shown to have an important role in Antarctic ozone destruction. They form in the lower stratosphere during the cold winter months, and can be composed of water ice or Nitrogen compounds, depending on the formation temperature. PSCs provide a surface for chemical reactions to take place that lead to chlorine free radicals, which are destructive to ozone (*Crutzen and Arnold*, 1986). PSCs also prolong these chemical reactions through denitrification, and thus play an important part in explaining massive ozone loss in the Antarctic (*Fahey et al.*, 1990). Understanding PSC formation, distribution, and movement is central to comprehending and predicting ozone loss (*Poole and McCormick*, 1988).

One way that has been proposed to study Polar stratospheric clouds is by using backscatter lidar. Lidar can detect the presence of PSCs and gather data used to infer particle size, which can then be used to study radiative effects of the clouds. A collaborative group of researchers from NASA Goddard Space Flight Center (GSFC) and Montana State University (MSU) have proposed to build an autonomous, ground-based backscatter lidar and install it on the Antarctic plateau to study PSCs. The lidar would be self-contained with enough battery power to last through the Antarctic winter. Clever power budgeting would allow it to take data on the order of minutes and relay that data via satellite back to ground stations in the United States. The entire system would have to be robust enough to operate in the harsh Antarctic environment, where ambient temperatures are expected to range between -20 and -80 degrees Celsius. To conserve power, very little active thermal control will be done, though passively controlled electronics boxes will be available at temperatures between -20 and -40 degrees Celsius.

The proposed lidar will take advantage of a fiber optic laser amplifier to produce the powers necessary from the transmitter. Fiber optic laser amplifiers typically use a single-mode glass fiber that has been doped with one or more rare-Earth elements. Different elements are used to produce light at different wavelengths. Erbium is typically used in telecom components, since it provides gain at 1550 nm, in the low-loss window of silica fibers. Ytterbium has a large gain bandwidth between 880 nm and 1000 nm, with a large peak around 975 nm. Emission can occur most efficiently near 975 nm or between 1.02 microns and 1.07 microns. Gain is achieved by emission from the doped Ytterbium ions when the amplifier is pumped into a state of population inversion. Ytterbium can be classified as having a three-level energy scheme. The doped ions are excited to a higher energy state by absorption of pump photons and then relax rapidly to a lower, stable energy state with lifetimes on the

order of milliseconds. This stored energy can then be released through stimulated emission by a seed source, which effectively transfers energy from the pump to the seed.

Fiber amplifiers have several advantages over conventional free-space amplification of light as is typically used in operational lidars. Fiber amplifiers allow high gain in a small package, since the fibers, which may be up to several meters long, can be coiled into bundles. The only limit to size is the bend radius, which needs to be sized so as to not allow light leakage or cause attenuation effects within the amplifier. This radius is typically around 10 to 20 cm. Fiber amplifiers do not use free-space optics, such as mirrors, lenses, or filters, as all of the necessary optical components can be contained within the fiber optic itself. In this manner, the transmitter always remains aligned, regardless of the direction and movement of the fiber. This makes a fiber amplifier-based lidar very vibration resistant, and therefore ideal for field deployments.

Another advantage of fiber optic laser amplifiers is that they are a mature technology. Fiber amplifiers have been in worldwide use in the telecommunications industry for over a decade now. Optical fiber amplifiers were actually invented in 1964 by E. Snitzer, who created a Neodymium doped amplifier operating at 1.06  $\mu\text{m}$ , and were looked at for transmission systems as early as the 1970's (*Becker et al.*, 1999). Fiber amplifier components are widely available and have low failure rates. The Technology Readiness Level (TRL) for these devices is high, making them a good candidate for field instruments.

This section describes a prototype Ytterbium-doped fiber optic laser amplifier that was built at GSFC during the summer of 2005, and is organized as follows. The next section discusses the lidar equation calculations used to set the initial lidar system parameters. Then a description of the simulation software is presented, with an explanation of how the gain fiber length was determined. Next, the construction

of the fiber amplifier is presented. Following that, simulated and measured results for the system are presented, as well as a discussion of possible reasons for discrepancies between the two. Finally, suggestions for future work are offered. The section is concluded with concluding remarks.

### Lidar Equation Calculations

The first step in designing the GSFC Antarctic polar stratospheric cloud lidar was to use the lidar equation (equation 2.1) to determine what system parameters would be needed to produce scientifically valuable data from the desired target. Questions that needed to be answered before design and construction could begin included determining what type of detector to use, if frequency-doubling was required or desired, what laser frequency was most advantageous to operate at, and what power, pulse repetition frequency (PRF), pulse width, averaging time, and receiver area to use.

A spreadsheet was created (Lidar\_equation.xls) that allows the user to input system and atmospheric parameters and calculates the expected daytime and nighttime signal-to-noise ratio (SNR) for a specified altitude. Through use of this spreadsheet, it was determined that the desired wavelength to use is 1064 nm, due to the large number of well-tested and easily available parts for this common wavelength. Running through the calculation showed that a nighttime SNR of 37.7 and daytime SNR of 1.83 could be achieved at a range of 20 km using a PRF of 7500, 1  $\mu s$  pulse widths, a 200 pm bandpass filter, 20  $\mu J$  of energy per pulse, and averaging for 5 minutes. 5 inch diameter athermal telescopes already field tested by GSFC scientists will most likely be used on the receiver side. A detector efficiency of 2% was assumed, because high-efficiency detectors for 1064 nm are difficult to manufacture and therefore not easily available. Several communications with Perkin-Elmer occurred discussing the

possibility purchasing a custom-made detector optimized for this wavelength. Perkin-Elmer was responsible for a similar detector used on the Geoscience Laser Altimeter System (GLAS) launched into orbit aboard ICESat in 2003. With the wavelength picked and calculations completed on the feasibility of the lidar system, design work began on the fiber amplifier.

### Gain Fiber Length Determination

Once the requirements of the Antarctic lidar were known from lidar equation calculations, a model of the fiber amplifier's performance was desired to expedite and optimize construction. Liekki, the company supplying the highly-doped Ytterbium gain fiber, provides software for modeling the performance of their products in fiber amplifiers. This software, Liekki Application Designer v2.0 (LAD) was used to design the fiber amplifier described in this paper.

LAD employs a graphical user interface that allows the user to place different components onto a workspace, connect them together with fiber optic cables, run simulations, and view results at any component-fiber juncture. Components include optical isolators, seed and pump diode lasers, filters, couplers, wavelength division multiplexers (WDM's), reflectors, gratings, fiber bundles, and Ytterbium and Erbium highly-doped single and double-cladding gain fibers. Results available are seed power, pump power, and Amplified Spontaneous Emission (ASE) power, all given in decibels relative to 1 mW (dBm). Properties for each component can be loaded from pre-stored files or input manually and changed between every simulation. Simulations typically take between a few seconds and a few minutes depending on model complexity. All simulations assume that the lasers are operated in CW mode. It has been reported that future versions of LAD will contain the option of pulsing lasers

(See <http://www.liekki.com>).

LAD was initially used to determine through simulation the optimal gain fiber length to be used in the final fiber amplifier. Three fiber amplifier models were built and simulated: the fiber amplifier design that was actually built, the actual design minus the 1064 nm isolator, and a version of the amplifier utilizing 4 W unstabilized Liekki pump diodes instead of the Bragg grating-stabilized 200 mW QPhotonics pump diode lasers. The length of the gain fiber was the only variable being changed between simulations.

The data for the fiber amplifier model that was actually built are shown in figure A.1. Results for the other two modeled amplifiers are contained in the spreadsheet file

YDFA\_Gain\_Fiber\_Length.xls for future reference. Parameters for each component were taken from the actual data sheets of the parts used. It was assumed that the pump lasers and seed laser were being run at maximum power (150 mW and 200 mW, respectively). The simulation showed that the output of the fiber amplifier reached a maximum of 25.453 dBm at a gain fiber length of about 8.5 cm. The simulation also indicated that the fiber amplifier output did not decrease with further increases of gain fiber length, which is a puzzling result, as the high absorption and losses in the fiber should begin to attenuate the output signal. Nonetheless, care was taken in the construction of the fiber amplifier to keep the gain fiber length above this limit of 8.5 cm, with less attention trying to achieve an actual length of exactly 8.5 cm.

It should be noted that simulations were performed for optimal gain fiber length of a second stage amplifier, which adds two more pump diode lasers and a second stage of gain fiber to the output of the first stage. These results are also contained in the file YDFA\_Gain\_Fiber\_Length.xls, to be used if the decision is made to add a second stage to this amplifier in the future.

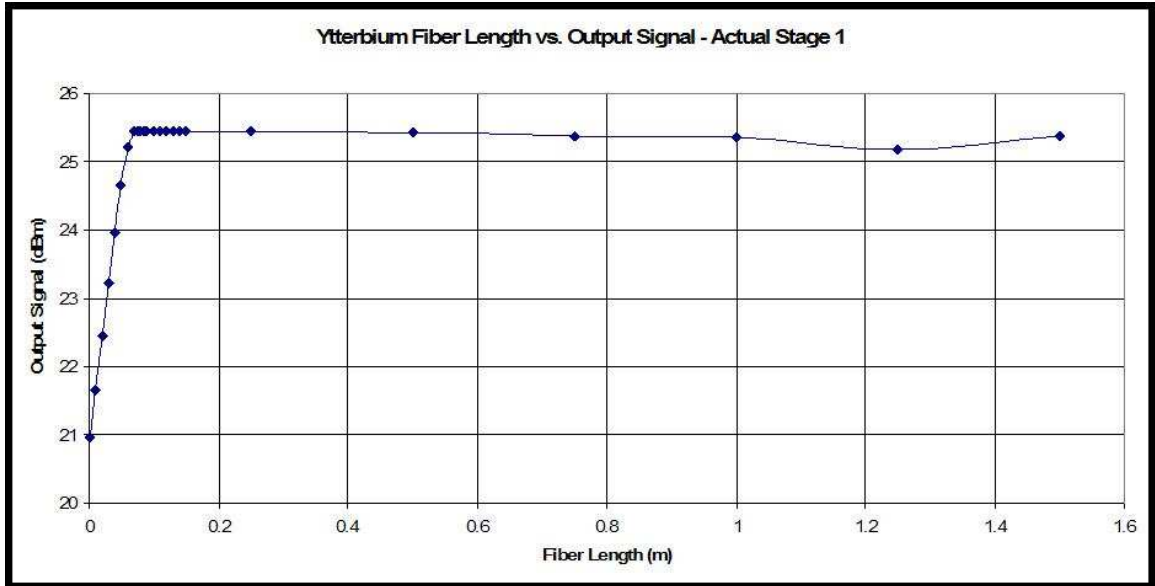


Figure A.1: Simulated output signal of the Ytterbium gain fiber versus length.

### Fiber Amplifier Construction

After the gain fiber length simulations, the Liekki Application Designer was used to simulate the three phases of construction of the actual fiber amplifier. The first phase, Construct 1, spliced a Bragg grating-stabilized, 150 mW pump laser (QPhotonics QFBGLD-980-150) running at 975 nm to a 980/1060 WDM. This acts as the forward pump. A Bragg grating-stabilized, 200 mW seed laser (Lumics LU106M200) running at 1064.6 nanometers was spliced to a polarization insensitive single stage isolator (Advanced Fiber Resources PSSI-06-P-N-B-1), which was subsequently spliced to the 1060 nm input of the WDM. Construct 1 is shown schematically in figure A.2.

All fiber splicing was performed using a Vytran FFS-2000 Automated Fusion Splicing Workstation. Most of the fibers were spliced by the author after being trained on this apparatus. The Vytran workstation automates all of the steps needed to create a robust, high-quality fiber splice: stripping the fiber coating to reveal the bare glass fiber, cleaning the fiber of all particulates, accurately cleaving the fiber end,

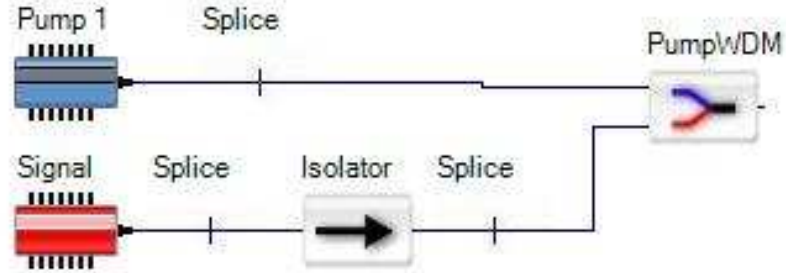


Figure A.2: A schematic of Construct 1.

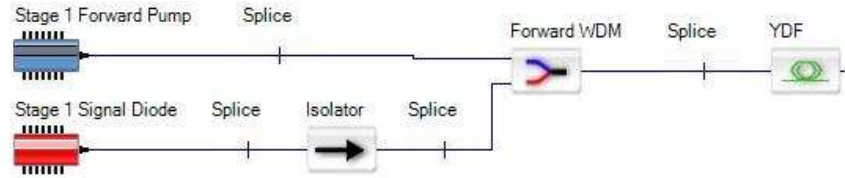


Figure A.3: A schematic of Construct 2.

computer-aided aligning and fusion of the fibers using a Tungsten lamp, and recoating the splice with a UV-cured coating material. With practice, several splices can be completed within one hour.

The second phase, Construct 2, spliced 21.0 cm of highly-doped Yb gain fiber to the output of the WDM. The length of the fiber was chosen to allow for multiple splices to be made while still keeping the length of the gain fiber above 8.5 cm, since each splice removes  $\sim 2$  cm from the fiber due to cleaving. Construct 2 is shown schematically in figure A.3.

The third and final phase, Construct 3, spliced an identical QPhotonics pump laser diode to the 980 nm input of an identical WDM as used in Construct 1. This acts as the reverse pump. The output of the WDM was then spliced to the free end of the gain fiber, which was reduced to 19.0 cm total length in the process. A

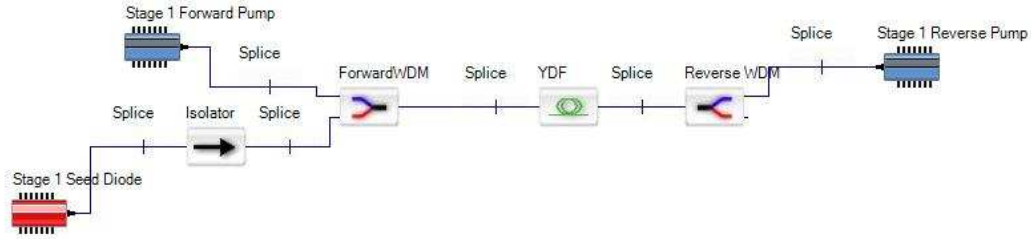


Figure A.4: A schematic of Construct 3. This schematic represents the final fiber optic laser amplifier design used for testing.

single-mode FC connector was spliced to the 1060 nm input of the WDM, making this the output of the fiber amplifier. The FC connector was used to make measurement acquisition easier. Construct 3 is shown schematically in figure A.4.

### Simulated and Measured Results

Construct 1 The Liekki Application Designer was used to simulate the three phases of construction of the actual fiber amplifier to compare its expected performance with actual measured results. The simulated and measured results for Construct 1 are shown in Table A.1 below. Both lasers are being run at optimum operating current, 450 mA for the seed laser (corresponding to 200 mW) and 250 mA for the pump laser (corresponding to 150 mW).

P-I curves and spectra were taken at this point for both the seed laser and the forward pump laser. The results are shown in figures A.5, A.6, A.7, and A.8, respectively. Only one laser was running at a time when the P-I curves and spectra were taken. The lasers were placed in 14-pin diode mounts (Thorlabs LM14S2 for the seed and reverse pump lasers and ILX LDM-4980 for the forward pump). Current

| Amplifier Output Power at 1064.6 nm | dBm         | mW          |
|-------------------------------------|-------------|-------------|
| Simulated                           | 21.24030004 | 133.0546337 |
| Measured                            | 20.51152522 | 112.5       |
| Amplifier Output Power at 975 nm    | dBm         | mW          |
| Simulated                           | 21.54091495 | 142.5907964 |
| Measured                            | 21.58663981 | 144.1       |

Table A.1: A comparison between the simulated and measured amplifier output powers for Construct 1 at the wavelengths of 1064.6 nm and 975 nm.

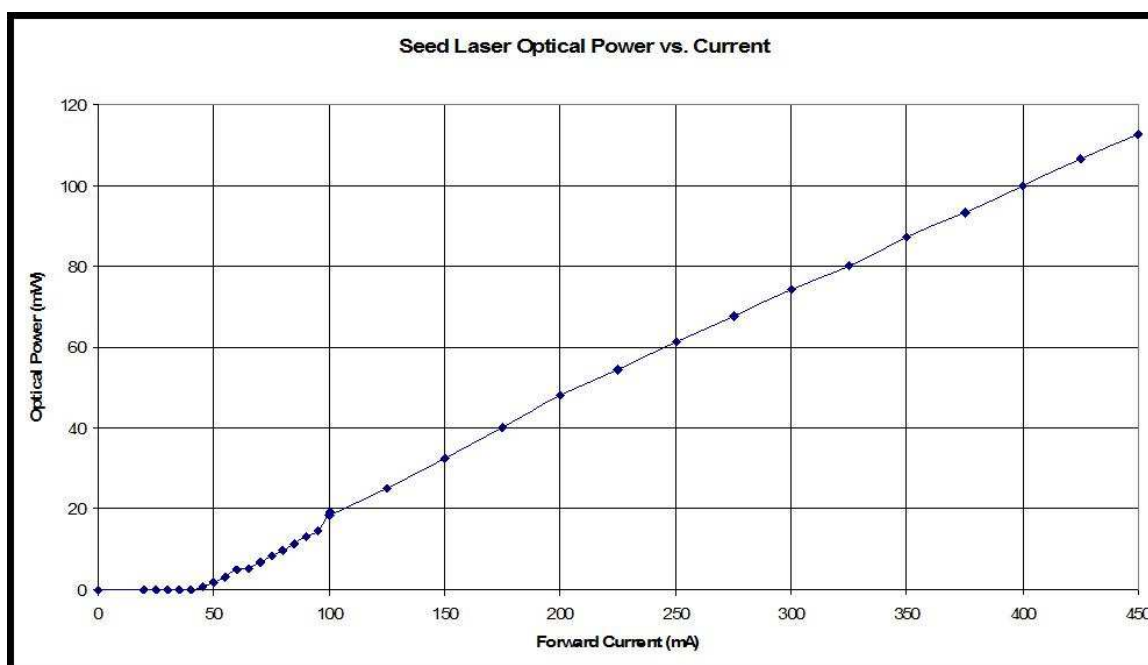


Figure A.5: P-I curve for the seed laser.

was provided by Thorlabs LD3000 current drivers. Temperature was controlled by ILX LDT-5100 temperature controllers. Both laser TEC's were held steady at 25 degrees Celsius. The bare fiber of the forward WDM output was aligned with a power detector for the P-I measurements and input into an OSA to measure the spectra.

From the P-I curves, it was determined that the power from the seed and pump lasers after the WDM was 112.5 mW and 144.1 mW, respectively. The seed power was considerably lower than the 200 mW that was presumably being fed into the

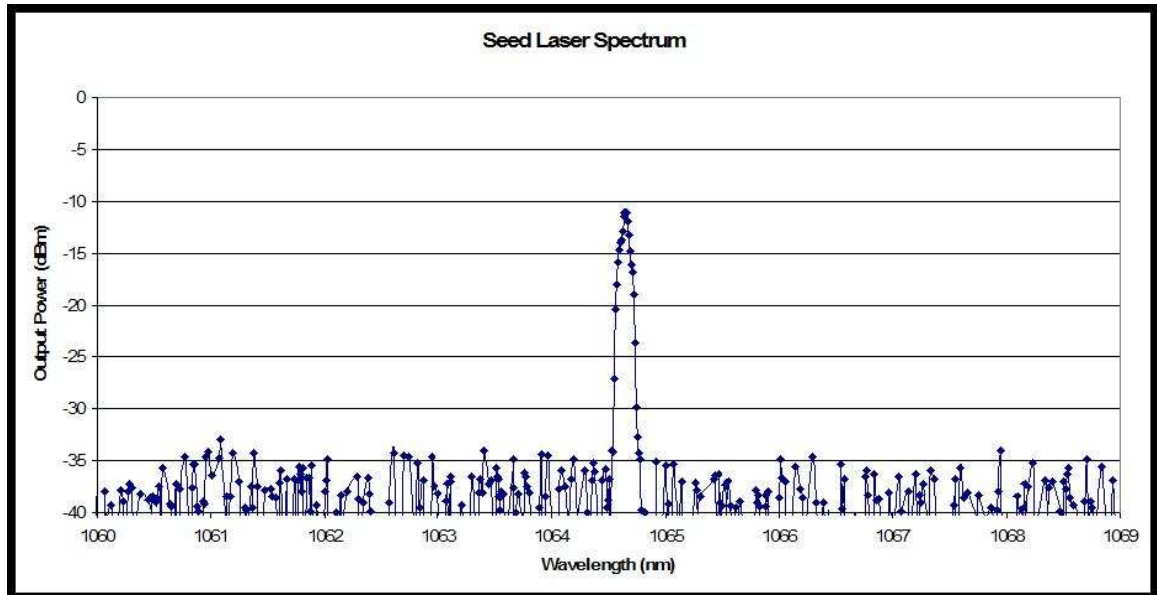


Figure A.6: Spectrum of the seed laser.

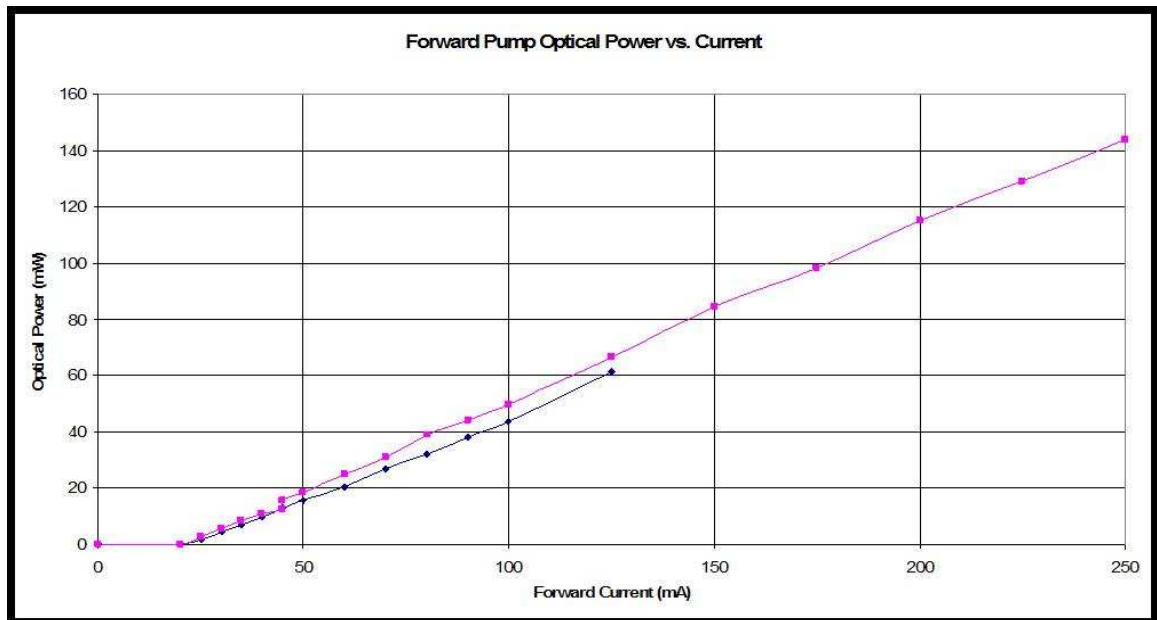


Figure A.7: P-I curve for the pump laser. A neutral density filter was used to obtain the data in pink.

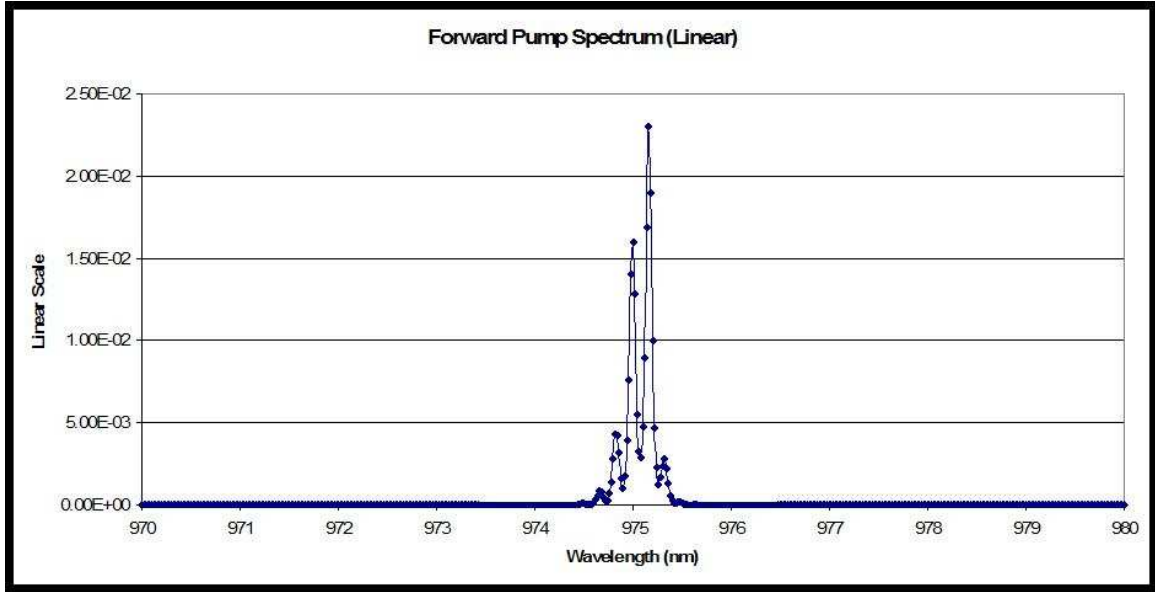


Figure A.8: Spectrum of the pump laser.

amplifier, and was probably attenuated heavily by the isolator. Since these powers were experimentally measured to be the input powers to the gain fibers, the LAD model was modified for simulations beyond this point to reflect these measured powers. To accomplish this in the model, the power parameter of the seed laser was set to 169 mW (down from 200 mW for Construct 1) and the pump laser power parameter was left unchanged at 150 mW. These parameters give the “correct answer” for input powers into the gain fiber in the forward direction. A P-I curve was not taken for the reverse pump diode, as it was assumed to be identical to the forward pump diode.

Construct 2 The simulated and measured results for Construct 2 are shown in Table A.2 below. Again, both lasers are being run at optimum operating current and the TEC's were held steady at 25 degrees Celsius. All pump power above the noise floor was absorbed in the gain fiber.

The measured power at this point shows gain but not nearly as much as the LAD

| Amplifier Output Power at 1064.6 nm | dBm         | mW          |
|-------------------------------------|-------------|-------------|
| Simulated                           | 23.58927244 | 228.5215939 |
| Measured                            | 20.79181246 | 120         |

Table A.2: A comparison between the simulated and measured amplifier output powers for Construct 2 at the wavelength of 1064.6 nm.

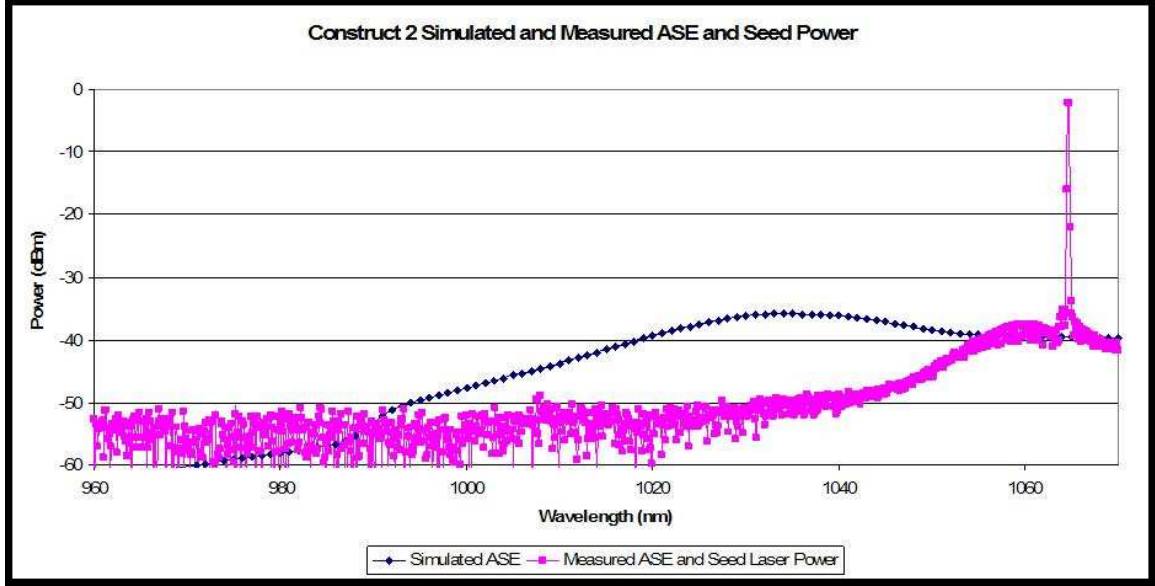


Figure A.9: Simulated and measured ASE of Construct 2.

simulation predicted. One difficulty in making this measurement was that the power meter used seemed to have a position-sensitive detector head. Different powers were measured depending on where the fiber was aimed on the detector. 120 mW was a consistently repeatable value, so it was used, even though it was on the lower end of all power values observed. The predicted ASE did not match the measured ASE either, as shown in figure A.9.

Construct 3 The simulated and measured results for Construct 3 are shown in Table A.3 below. All three lasers were run at optimum operating current and the TEC's of the pump lasers were held steady at 25 degrees Celsius. The seed laser

required tuning to remain single-mode at 1064.6 nm, and a voltage of 557.4 mV was monitored on the TEC. All pump power was again absorbed into the gain fiber.

| Configuration         | Simulated Power (mW) | Measured Power (mW) | % difference |
|-----------------------|----------------------|---------------------|--------------|
| Seed Laser Only       | 67.78330154          | 61.2                | 9.7          |
| Seed and Forward Pump | 177.5027186          | 101.2               | 43.0         |
| Seed and Reverse Pump | 194.580914           | 113.3               | 41.8         |
| Seed and both pumps   | 283.0100864          | 160.4               | 43.3         |

Table A.3: A comparison between the simulated and measured amplifier output powers for Construct 3 in different configurations at the wavelength of 1064.6 nm.

Power measurements were easier to make at this point because of the use of a FC connector versus the bare fiber, as in Construct 2. The amplifier showed gain when operated with both pumps or individual pumps. It showed slightly more gain when operated with the individual reverse pump than with the individual forward pump, and displayed about 4 dB of gain over the seed laser only with both pumps at full power. However, the wide difference between the LAD-simulated gain and the measured gain is disturbing. The measured performance does not seem to be even close to the performance that was expected based on simulations. Figure A.10 shows a spectrum of the predicted performance versus the measured performance.

An attempt was made to pulse the seed laser and obtain pulse energy measurements. Unfortunately, a suitable pulse driver was not immediately available to drive the seed laser. Custom pulse driver cards have been built and used successfully with other diode lasers at GSFC, but there were no cards available that could drive the seed laser with enough current. Therefore, no pulse energy measurements were obtained.

Several problems have been suggested for explaining the discrepancies between the simulated results and the measured results. First, there may be a problem with the LAD simulation not including an important loss or nonlinear effect that is reducing the overall power output. As stated before, it is troubling that LAD simulations show

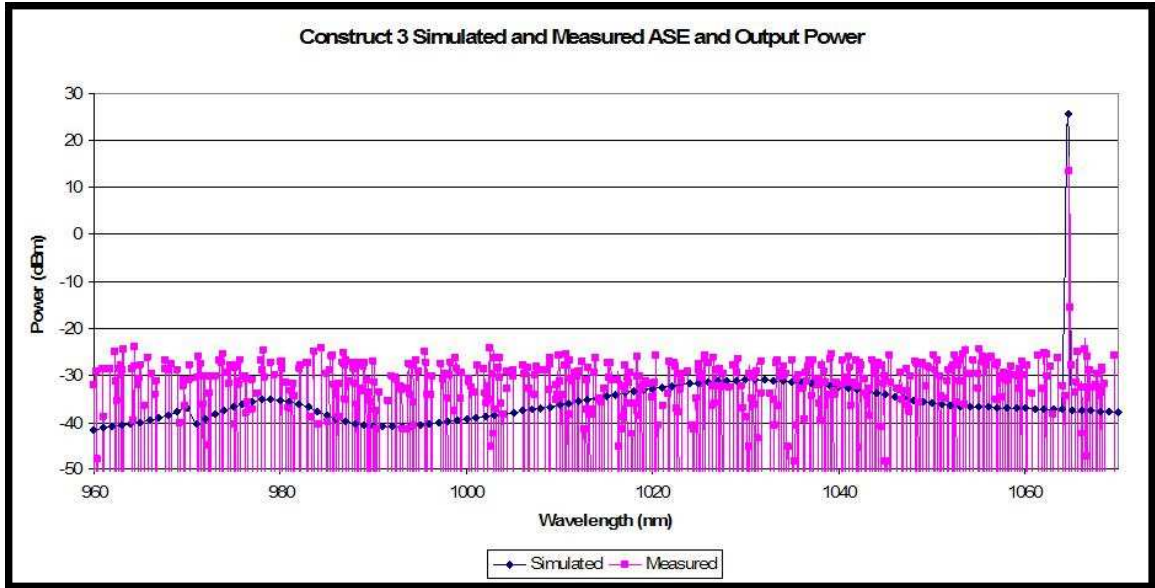


Figure A.10: Simulated and measured results of the system.

no loss of signal when using any length of gain fiber between 8.5 cm and 1.5 m. It may be likely that significant loss is present immediately above 8.5 cm and using 19.0 cm of highly-doped gain fiber is significantly attenuating the signal. A problem in the gain stage of the fiber amplifier seems to be indicated by looking at the measured gain curve, shown in figure A.11. The curve does not have a step-function characteristic as expected of fiber amplifiers. As of this writing, the author has been in contact with software technicians at Liekki to insure that the simulation parameters used match the real situation.

Second, there are indications that the pump lasers are interfering with each other. When one pump is already operating at full power and the power of the other pump is slowly increased, an interaction is visible through an IR viewer. The light leaking out of the fibers from one pump immediately decreases in a discontinuous manner when the other pump laser's power is increased just above threshold. It is possible that the two pumps and their respective gratings are creating a laser cavity, reducing

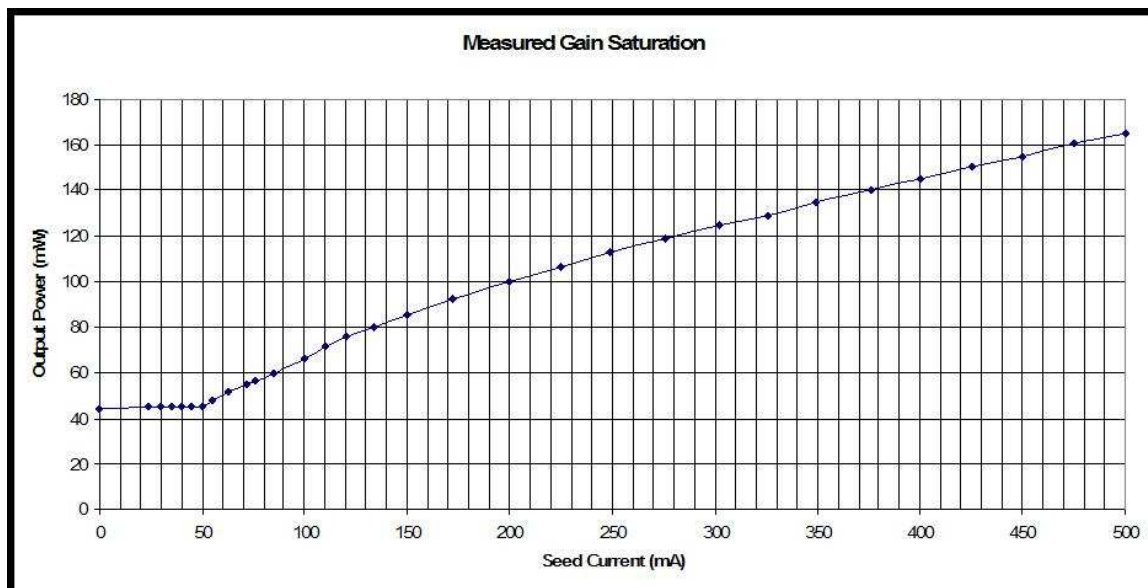


Figure A.11: Measured gain curve of the fiber amplifier.

the pumping efficiency and therefore reducing the overall amplifier gain. Evidence of this is seen when the pump lasers are running at full power and the input seed laser power is just above threshold. The amplifier seems to be trying to lase at about 1023 nm. This behavior appears whenever one pump is running at full power, and the other is at any power above threshold.

Third, there may be a currently undiscovered source of excessive loss in the fiber amplifier. Each fiber splice was verified to be of high quality during the construction process. Yet, damage may have occurred to a component, fiber splice, or to the fiber itself. Loss may be occurring due to the fiber being wound too tightly in some places. More investigation is needed to find the source of these problems.

### Future Work

Three distinct action items need to be completed to move this project forward. First, 975 nm isolators should be purchased and installed on the pump laser lines. This

should eliminate any interference between the pump lasers. Second, the optimized gain fiber length needs to be understood. Conversations with Liekki and further LAD simulations should show unequivocally whether there is a performance difference between using 8.5 cm or 19.0 cm of gain fiber. This should eliminate questions about the efficiency of the gain stage. Third, a pulse driver board needs to be built and optimized for pulsing of the seed laser. The Lumics seed laser can be operated with currents up to 2 A, with a 30  $\mu s$  period and 300 ns pulse widths. This current needs to be taken advantage of to increase the power of the system. Accomplishing these three tasks should eliminate any questions about the gain of the amplifier and allow lidar data to be taken. At that point, discussion should begin on whether a second gain stage is needed for completing the science goals in Antarctica.

### Conclusion

Design, simulation, construction, and testing of a highly-doped Ytterbium-based fiber optic laser amplifier for measuring Antarctic polar stratospheric clouds is well underway at Goddard Space Flight Center. A prototype fiber amplifier has been built and is currently undergoing testing. Initial testing showed that gain was achieved producing an output power of about 160 mW, which was, however, much lower than the 283 mW output power predicted through simulations. Several problems have been suggested that may be reducing the gain, and solutions are being investigated. It is hoped that after further testing and optimization of this amplifier, a prototype of the Antarctic PSC lidar can be deployed in Alaska for field testing before being installed in Antarctica.

APPENDIX B

MAXIMUM PERMISSABLE EXPOSURE (MPE) LIMITS AND FEDERAL  
AVIATION ADMINISTRATION (FAA)  
APPROVALS

## Introduction

Proper laser safety requires that all personnel involved with the operation of a laser be aware of the power output of that laser, and whether it exceeds the maximum permissible exposure (MPE) level for the human body. The MPE is the irradiance [ $W/cm^2$ ] or energy density [ $J/cm^2$ ] threshold that has been determined to not damage certain body tissues. The MPE depends on many factors, including the type of laser (pulsed or cw), the laser wavelength, pulse energy and pulse width, and the type of tissue upon which the laser is incident. For example, the MPE level for skin tissue is typically higher than the MPE for laser light that reaches the eye, since light that is not absorbed by the cornea will be focused onto the retina by the eye's lens. The calculations for determining MPE are typically somewhat nonintuitive. The wavelength plays a crucial role in the calculations since the human eye has a natural blink response for visible wavelengths, but none for wavelengths in the near infrared. Near IR calculations therefore must take this factor into account. Further into the IR, near telecommunications wavelengths of 1550 nm, the MPE for the human eye changes dramatically since these longer wavelengths can no longer penetrate the cornea and be focused onto the retina. Calculating the MPE for pulsed lasers tends to be much more difficult than cw lasers. Fortunately, detailed descriptions of the restrictions and calculations are given in the *ANSI National Standard for Safe Use of Lasers* (ANSI Z136.1-2000). All information and calculations described herein were taken from this source.

ANSI Z136.1-2000 applies to lasers with wavelengths between 180 nm and 1 mm and is full of useful safety information for anyone involved with lasers. It defines the five classes of lasers. Class 1 lasers present no hazards to people and require no controls. Class 2 lasers are visible lasers ( $400\text{ nm} < \lambda < 700\text{ nm}$ ) that emit  $< 1\text{ mW}$

of radiant power. Eye protection for this class comes from the natural blink reflex and aversion response. Class 3 lasers are hazards under direct or specular reflection, but not diffuse reflection, and are split into two categories. Class 3a lasers have outputs between 1 and 5 times the Class 1 Accessible Emission Limit (AEL, the maximum emission permitted) for  $\lambda < 400$  nm or  $\lambda > 700$  nm, or less than 5 times the AEL in visible wavelengths. Class 3b lasers exceed the ultraviolet ( $\lambda < 400$  nm) or infrared ( $\lambda > 700$  nm) or visible output of Class 3a lasers but not above an average power of 0.5 W for  $\geq 0.25$  seconds or energy of 0.125 J in  $\leq 0.25$  seconds. Because the output of the amplified diode laser transmitter used in the DIAL instrument is greater than 1 mW but less than 0.5 W, it is classified as a Class 3b laser. Class 4 lasers are dangerous under direct, specular, and diffuse reflection and are fire hazards. This classification includes any laser above Class 3b. Other useful definitions are included as well. Continuous-wave (cw) lasers are defined as lasers that have a continuous output for a period  $\geq 0.25$  seconds, since the eye does not have a blink response for shorter pulses. Beam radius is measured between the point with peak power per unit area and the point where the power per unit area drops to  $1/e$  of this maximum value.

Lasers being operated in the open atmosphere where civilians unaware of laser safety or the laser itself may be exposed, such as in lidar transmitters, require special considerations to ensure that no one is harmed. Lidars in general usually need to be approved for operation by the Federal Aviation Administration (FAA) to ensure safety to pilots and aircraft passengers. A number of bureaucratic steps and mathematical calculations are needed to obtain approval. Outdoor lasers are now governed by FAA Order 7400.2F, *Procedures for Handling Airspace Matters*, Part 6, Chapter 29. As of February 2007, this document could be found by doing a search on the FAA's website, [www.faa.gov](http://www.faa.gov), or more specifically at [http://www.faa.gov/airports\\_airtraffic/air\\_traffic/publications/atpubs/AIR/index.htm](http://www.faa.gov/airports_airtraffic/air_traffic/publications/atpubs/AIR/index.htm).

### Obtaining FAA Approval

The steps for getting a laser approved for firing outdoors are: 1) Contact the FAA, 2) Calculate the minimum eye-safe altitude, 3) Obtain independent confirmation of calculations, and, 4) Notify the FAA of the calculation results, the independent reviewer, and all necessary information on location and date and time of laser operation. This appendix explains the steps and calculations taken from the ANSI Standards and performed to find the MPE levels and originally approve the water vapor DIAL instrument for outdoor use.

### Contacting the FAA

The first step towards approval for vertical operation is to contact the FAA and notify them of the initial characteristics of the laser. As of August 2004, Bozeman, MT was governed by the Northwest region of the FAA, whose headquarters are in Seattle. The contact I worked with for these calculations was Kathie Curran. In conversations I had with her at that time, she indicated that approvals for the Bozeman area would soon be handled through Los Angeles International Airport, so her contact information is likely no longer valid. She also indicated that the person who would be replacing her for these types of permissions is Gordy Burnet and that the official at FAA headquarters in charge of lasers is Steve Rohring. The person that we are working with to obtain permissions as of February, 2007, is Rick Roberts, a FAA system support specialist in Renton, Washington. Contact information for these four people is given in tables B.4 and B.5.

|          |                       |                      |                         |
|----------|-----------------------|----------------------|-------------------------|
| Contact: | Kathie Curran         | Gordy Burnet         | Steve Rohring           |
| Email:   | Kathie.Curran@faa.gov | gordy.burnet@faa.gov | stephen.rohring@faa.gov |
| Phone:   | (425) 227-2558        | (425) 227-2535       | (202) 267-9231          |
| Fax:     | 425-227-1530          | 425-227-1530         |                         |

Table B.4: Contact information for the FAA that I used in 2004.

|          |                         |
|----------|-------------------------|
| Contact: | Rick Roberts            |
| Email:   | Richard.Roberts@faa.gov |
| Phone:   | (425) 917-6728          |
| Fax:     | 425-917-6476            |

Table B.5: Contact information for the FAA, current as of February, 2007.

To begin the approval process, the FAA wants to know at least the laser's location (latitude and longitude), the eye-safe altitude, and the date and time of operation. For MSU, the coordinates were given for the top of the roofport room, at the Southeast corner of the roof of Cobleigh Hall (found using a hand-held GPS unit):

45 degrees, 39.984' North, 111 degrees, 2.744' West, 5003 +/- 18.3 feet.

Ms. Curran indicated that decimals should not be used in the coordinates, all distances should be expressed in feet instead of meters, and the ground-level altitude according to her calculations should be 4924 feet. Our updated coordinates for FAA purposes therefore are:

45 degrees 39' 59" Latitude, 111 degrees 02' 44" Longitude, 4924 feet elevation.

Using the latitude and longitude coordinates of the laser, the FAA will determine its proximity to airports and designate which of four flight zones the lidar occupies. This in turn defines the laser irradiance level that must be adhered to. The flight zones are defined in FAA Order 7400.2E and are listed with their defining characteristics in table B.6. It was determined with mapping software using the FAA latitude and longitude coordinates for Gallatin Field airport that the roofport room in Cobleigh

| Zone                  | Distance to Airport *                                                        | Max. Irradiance Level         |
|-----------------------|------------------------------------------------------------------------------|-------------------------------|
| Laser Free Zone       | 2 NM radial from runway centerline<br>2500 feet each side of runway for 3 NM | $50\text{ nW/cm}^2$           |
| Critical Flight Zone  | 10 NM radial from airport reference point                                    | $5\text{ }\mu\text{W/cm}^2$   |
| Sensitive Flight Zone | Outside Critical Flight Zone having<br>special restrictions                  | $100\text{ }\mu\text{W/cm}^2$ |
| Normal Flight Zone    | Airspace not defined by other zones                                          | $MPE$                         |

Table B.6: Specifications of the FAA's four flight zones. (*\*Note that minimum altitude requirements for these irradiance levels also apply.* NM=Nautical Mile)

Hall, where most vertically-viewing lidar work occurs, is located a distance of 9.25 miles (14.89 km, 8.04 nautical miles) from the airport, placing it in the Critical Flight Zone.

#### Minimum Eye-safe Altitude Calculations

The goal of the next step is to use the ANSI Standards to find the most conservative MPE level for the laser, and then calculate the minimum altitude where beam divergence causes the laser beam to fall under this irradiance level, making it eye-safe. The eye-safety calculation that must be done depends on whether the laser that is being operated is cw or pulsed.

CW Lasers For cw lasers, the average power and beam area must be known so that an irradiance can be computed by taking their ratio. This is then compared to an MPE level that is calculated with help from the ANSI Standards, which takes into account cumulative damage to tissue based on exposure time. For visible wavelengths, a maximum ocular exposure time of 0.25 seconds can be used due to the eye's natural aversion response. For UV or IR wavelengths, a maximum exposure time of 10 seconds is assumed based on natural movements of the eye, which limit the exposure time.

Since all MSU lidars to date rely on pulsed lasers for operation, cw MPE calculations will not be discussed.

Repetitive Pulse (RP) Lasers MPE calculations for pulsed lasers are significantly more complicated than for cw lasers. Three rules must be followed. First, the exposure from any single pulse cannot exceed the MPE level. This rule protects against thermal damage due to any single pulse having greater than average energy. The specifications for the water vapor DIAL transmitter are given in table B.7. The pre-

| Specifications               | Preliminary      | Actual            |
|------------------------------|------------------|-------------------|
| $\lambda$                    | 830.0 <i>nm</i>  | 828.187 <i>nm</i> |
| Pulse Length                 | 1.0 $\mu s$      | 500.0 <i>ns</i>   |
| Repetition Rate              | 10.0 <i>kHz</i>  | 20.0 <i>kHz</i>   |
| Average Power                | 500.0 <i>mW</i>  | 200.0 <i>mW</i>   |
| Pulse Energy                 | 500.0 <i>nJ</i>  | 100.0 <i>nJ</i>   |
| Beam Divergence (full angle) | 1.43 <i>mrاد</i> | 150 $\mu rad$     |

Table B.7: Values used for the maximum permissable exposure calculations.

liminary specifications were used in the calculations for the original approval of this system. The actual specifications of the final operational system as of February, 2007, are given for comparison. From table 5a of the ANSI Standards, the MPE for a laser of these specifications (specified in  $J/cm^2$ ) is

$$MPE = 1.8 \times 10^{-3} \cdot C_A \cdot t^{0.75}, \quad (B.1)$$

where  $t$  [seconds] is the exposure time and  $C_A$  [unitless] is a correction factor defined in table 6 of the ANSI Standards as

$$C_A = 10^{2(\lambda - 0.7)}. \quad (B.2)$$

With  $C_A = 1.82$  for the wavelength of 830 nm and a single-pulse exposure time of  $t = 1.0 \mu s$  the single-pulse MPE is  $MPE_{SP} = 1.04 \times 10^{-7} J/cm^2$ .

Second, the exposure from any group of pulses delivered in a time  $t$  cannot exceed the MPE level for that time. This rule protects against cumulative injury from photochemical damage mechanisms and also against thermal damage caused by heat buildup from the laser average power. The maximum exposure limit for an IR laser, as discussed in the CW Lasers section above, is 10 seconds. With equation B.1, the MPE for this exposure time is  $MPE : H_{group} = 0.0184 J/cm^2$ . Averaging over the number of pulses in this exposure time, the average power limit becomes

$$MPE : H_{group}/pulse = \frac{(0.0184 J/cm^2)}{(10^4 pulses/sec) \cdot (10 sec)} = 1.84 \times 10^{-7} J/cm^2. \quad (B.3)$$

Finally, a third rule protects against cumulative injury from thermal buildup below the allowed threshold levels, and is defined as the single-pulse MPE from rule 1 multiplied by a multiple-pulse correction factor. With the total number of pulses being the same as calculated in rule 2, 100,000 over 10 seconds, the final MPE level is

$$MPE/pulse = n^{-0.25} \cdot MPE_{SP} = 5.85 \times 10^{-9} J/cm^2. \quad (B.4)$$

The MPE calculated from rule 3 gives the most conservative answer, and therefore must be used to determine the eye-safe altitude. The beam radius where the laser reaches the eye-safe MPE is calculated by solving the equation

$$MPE = \frac{(Pulse Energy) \cdot (Repetition Rate) \cdot (Exposure Duration)}{\pi(Beam Radius)^2}, \quad (B.5)$$

to find a value of  $Beam Radius = 1650 cm$ . The eye-safe altitude, assuming a circular beam, is where the divergence of the laser causes the beam radius to grow to

this size, or *Eye Safe Altitude* =  $(\text{Beam Radius})/\text{tangent}(\text{half-angle divergence}) = 23.1 \text{ km} = 75,787 \text{ feet}$ . Rounding the calculations upwards adds an extra safety factor to the calculations. This is the altitude that must be reported to the FAA, since each individual laser pulse will exceed the MPE level at any lower altitude.

It is important to note that even for a relatively low-power infrared laser the FAA-defined eye-safe altitude is over 14 miles above ground level! Due to its much smaller divergence angle, the actual system would have an even higher calculated eye-safety altitude, although the actual laser divergence will be larger than designed due to atmospheric turbulence. This altitude is far different than if the MPE calculations were performed simply by using the average power and divergence of the laser beam, where the maximum irradiance level of  $5 \mu\text{W}/\text{cm}^2$  for the Critical Flight Zone would be reached at an altitude of  $2495 \text{ m} = 8187 \text{ feet}$ . This enormous difference is primarily due to the assumption that any person looking into the beam is assumed to not avert their eyes for 10 seconds. Visible beams of the same specifications come to an eye-safe level much quicker because of the natural blink response. This is a problem for infrared lidar systems because the FAA typically will not grant permission to lasers that are not eye-safe below 20,000 feet since doing so would require high-altitude flight paths to be altered to avoid the beam. Permission to fire the MSU lidar system at 830 nm was only given because the divergence angle was expanded so that the eye-safe altitude was calculated to be under the 20,000 feet limit.

One way to possibly circumvent this problem in the future is to make the argument that the 10-second exposure limit is highly unlikely, since the beam is pointed vertically and the beam width is not very wide even at high altitudes, making the chances of a pilot finding the beam and staring into it for 10 seconds extremely improbable. For example, at the calculated eye-safe altitude the beam diameter is 33 meters across, meaning an aircraft would need to be flying at  $3.3 \text{ m/s}$  or less to remain

in the beam for 10 seconds or more, assuming it was flying directly across the center of the beam. With the average cruise speed of a small aircraft such as a Cessna 172 Skyhawk listed as  $\sim 60\text{ m/s}$ , it is highly unlikely that a small plane or jet would be in the beam for more than a fraction of a second. If the MPE is recalculated using a more realistic, but still very conservative, exposure time of 1 second, the eye-safe altitude drops to a much more reasonable value of  $5500\text{ m} = 18,045\text{ feet}$ . Further arguing that atmospheric turbulence limits the divergence angle to 1 mrad or more would make the eye-safe altitude even lower still.

#### Independent Confirmation of Calculations

After the calculations for minimum eye-safe distance have been performed, the FAA used to require that they be verified by an independent source. Calculations are now sent directly to the FAA contact in Washington for verification. If confirmation of MPE calculations is still needed, it can be done through a number of sources, including businesses who charge for the service, but the agency recommended by the FAA in 2004 was the Food and Drug Administration's Center for Devices and Radiological Health (CDRH), who are responsible for enforcing the Federal government's regulations concerning lasers. The person who was directly in charge of laser safety is a laser physicist in the CDRH Compliance Office, Dale Smith. He was very familiar with lasers and their safety calculations and verified the calculations for the MSU water vapor DIAL system. His contact information is given in table B.8.

|          |                     |
|----------|---------------------|
| Contact: | Dale Smith          |
| Email:   | lds@cdrh.fda.gov    |
| Phone:   | (301) 594-4654 x147 |

Table B.8: Contact information for the CDRH.

### Approval

Once the FAA has been notified of the calculation results, the independent reviewer, and the requested location, date, and time of laser operation, they will either disapprove or approve the request. Approval comes in the form of a “Letter of Non-Objection” which states the the allowed dates and times of operation and any safety stipulations required by the FAA. Common examples of stipulations include: having a phone line where operators can immediately be contacted by the FAA, having spotters watching for planes flying near the beam, and notifying whomever is on duty at the Air Traffic Control Tower (ATCT) at Gallatin Field Airport in Bozeman and the Air Route Control Center (ARTCC) at Salt Lake International Airport in Salt Lake City 30 minutes before commencing and upon shutting down. The Letter of Non-Objection lists the numbers to be used for contacting air traffic control (ATC). For MSU, the numbers are given in table B.9. Any changes in the lidar design or laser requires new approval before operation. The Letter of Non-Objection takes about 3 weeks to get all of the necessary signatures. A copy is typically faxed upon completion, with a hard copy mailed simultaneously.

|                                                  |                |
|--------------------------------------------------|----------------|
| Gallatin Field Airport (BZN) ATCT                | (406) 388-9082 |
| Salt Lake City International Airport (ZLC) ARTCC | (801) 320-2561 |

Table B.9: Contact information for airports in Bozeman and Salt Lake City, Utah.

### Conclusion

Obtaining and maintaining FAA approval for firing lidar systems is obviously a time-consuming, tedious, and somewhat confusing process, although it becomes easier once a particular lidar system is initially approved. The ideal situation would be to

ensure laser safety while circumventing the need for continual FAA approval, which can at times stand in the way of scientific objectives when interesting atmospheric conditions call for using a lidar that does not have current FAA approval. As of February, 2007, representatives of the FAA are insisting that human spotters on the roof of Cobleigh Hall are still necessary even with the installation of an X-band radar capable of detecting airborne vehicles near the MSU campus, although they are trying to get around this requirement. Until a solution for allowing lidar systems to be operated safely at any time is found that is suitable to both MSU and the FAA, lidars at MSU will continue to be subject to the FAA's approval and reapproval processes and restrictions.

APPENDIX C

DIAL OPERATING GUIDE

This appendix consists of a user's guide for operating the DIAL. The step-by-step directions for operation of the system are:

1. Make sure the APD power cord is disconnected.
2. Apply power to the power strip on instrument cart containing the wavemeter, power meters, MCS, AWG, AOM power supply, and fan power supply.
3. Turn on both power meters, wavemeter, the power supply to the AOM driver, the power supply to fan, and the AWG used to provide the pulsing waveform to the AOM driver. The wavemeter will take several up to 10 minutes to warm up. The 1830c power meter should be set to fast averaging by pushing the "AVG" button once, and should be set for use with the attached attenuator by pushing the "ATTN" button once. The wavemeter wavelength should be set to "Vacuum". The voltage to the AOM driver should 28 V. The fan that cools the second tapered amplifier should be supplied with about 20 V.
4. Verify that all wires are correctly connected, especially the signal BNC cable from the APD to the MCS, the power cables to the AOM driver, and the output BNC cable from the AWG to the AOM driver, as these tend to be disconnected or loosened more than other cables.
5. Turn on the two laser-tuning AWG's, and the piezo driver for the ECDL.
  - (a) Set channel 1 of the ECDL bias AWG (located on the left) to a sinusoidal waveform, with 0.1 V amplitude and 150 kHz frequency.
  - (b) Set channel 2 of the ECDL bias AWG (located on the left) to a dc bias waveform with an amplitude of -4 V.

- (c) Set channel 1 of the ECDL tuning AWG (located on the right) to a dc bias waveform and activate it. The amplitude of this waveform will set the wavelength to which the ECDL is tuned, as described in Chapter 5. Typical voltage values are 0.7 V for the on-line wavelength and 3.0 V for the off-line wavelength, although these are variable.
6. While waiting for the wavemeter to warm up, plug in the power to the laptop LidarLap1.
7. Connect the laptop to the USB-GPIB connector that is attached to the laser tuning and bias AWG's.
8. Activate power to the laptop, and login to the lidarlap1 user.
9. Start LabVIEW and open software dialv10.vi.
10. Create a new folder for writing data in E:\Vertical\_WV\_DIAL\Data\_runs with the current date in the format of MMDDYY, i.e. 010107 for January 1st, 2007.
11. When the wavemeter is ready to read the ECDL wavelength, make sure the optical fiber monitoring the ECDL is attached to the wavemeter and correctly aligned, switch the ECDL bias electronics box to “off” and activate power to the ECDL power supply. The power indicator on the wavemeter (provided the optical fiber monitoring the ECDL laser is correctly aligned and attached to the wavemeter) will jump from zero power to about 25%.
12. Activate channel 2 of the ECDL bias AWG, supplying full current to the ECDL. The power indicator on the wavemeter should now to about 75%. Note that the ECDL wavelength may jump by  $\sim 3$  nm, but should settle to between 828

nm and 833 nm if it is operating correctly. If the power drops to zero or is intermittent, it is most likely a grounding problem within the ECDL electronics box.

13. Activate channel 1 of the ECDL bias AWG, supplying a sinusoidal modulation to the ECDL for tuning purposes. Note that this step has been known to cause instabilities in the ECDL wavelength, running the wavelength quickly to 800 nm or 850 nm uncontrollably. If this is the case, deactivate the sinusoidal modulation and wait several minutes until the ECDL is more temperature-stabilized. The instabilities only seem to manifest themselves if applied to the ECDL before it has sufficient time to equilibrate with the environment. Generally, the longer the ECDL can be active without the sinusoidal modulation, the better it will behave.
14. Remove the tapered amplifier covers and activate the tuning reference power meter.
15. Turn on the lock-in amplifier. When the lock-in amplifier has found the tuning reference power meter signal, it will lock, at which point the output BNC cable can be attached.
16. Turn off the room lights.
17. Plug in the power cord for the APD at least 15 minutes before it is to be used. As with other instruments, the more warmup time the APD has, the better it will respond. It is good practice to leave the room lights off even though the APD should be protected at this point within its sealed box.
18. Open the roofport at least 15 minutes or more before use to stabilize the temperature and pressure within the room. This is especially critical when a large

temperature gradient exists between the inside and the outside of the building.

19. Verify that the 1930c power meter detector head is placed after the second amplifier-alignment iris, right before the second tapered amplifier, and activate the first tapered amplifier. The drive current should be set to roughly 2100mA to provide about 20-22 mW of seed power to the 1930c power meter.
20. Wait for the first TA to stabilize at about 20-22 mW seed power into the 1930c power meter. Using the two alignment mirrors immediately before the first TA, peak up its power using the 1930c power meter.
21. Apply the cw setting to the AOM driver AWG. This should be a dc offset of 1.5 V amplitude, and was saved in the AWG memory as memory slot 2, called “cw”.
22. Remove the 1930c power meter detector head and activate the second TA.
23. Verify that the second tapered amplifier cooling fan is being supplied with about 20 V, and increase the second TA drive current to about 1000 mA.
24. Using the two alignment mirrors immediately before the second TA, the z-axis stage for the second TA, and the focusing lens attached to a translation stage between the two alignment mirrors, peak up the output power of the second TA using the 1930c power meter detector head placed after the second TA. Adjusting the alignment of the second TA tends to be easier below full drive currents, which is why the second TA should be set to about 1000 mA at this time.
25. Use the 1930c power meter detector head to again check the seeding power incident on the second TA. Adjust the drive current of the first TA accordingly

so that the seed power is 20-22 mW. Note that the limit for seeding either tapered amplifier is 20 mW according to the manufacturer's specifications, but that not all of the power incident on the power meter actually is seeded into the gain region of the amplifier.

26. Remove the 1930c power meter detector head from the laser beam and increase the drive current to the second TA to a full power of about 2800-2900 mA. Note that the current limit is 3000 mA but that the tuning characteristics of the amplifiers seem to degrade when driven above about 2900 mA.
27. Verify that the reference power being measured by the 1830c is roughly 3-4% of the total output power of the second amplifier after the AOM. It is VERY IMPORTANT to note here that if the total transmit power is not as high as expected, it is almost always not a hardware or alignment problem, but most likely due to obstruction of the beam somewhere in the experiment. The transmit system stays well aligned over weeks of use, and small misalignments due to temperature variations or natural vibrations typically do not reduce the power by a large fraction. Thus, be sure to verify that the beam path is clear of obstruction before looking for a solution with misalignment or a hardware malfunction. Also, verify that all power and data cables are correctly connected, and that the AOM driver AWG is actually activated, all of which are common mistakes if the system is not transmitting.
28. Replace the top covering for the experiment to ensure that stray transmit laser light is blocked from the user and the telescope. At this point the system should be ready to take data using DIAL\_v10.vi!
29. When the experiment is ready to be stopped, first disable the AOM driver AWG,

so that the laser is no longer fully transmitting. Reduce the drive current on the second TA to about 1000 mA or less and disable it. Disable current to the first TA. Close the roofport.

30. Unplug the APD so that the room lights can be turned on.
31. Unplug the output BNC cable at the front of the lock-in amplifier. Shut down the lock-in amplifier. Disable the voltage to the piezo driver, channel 1 on the ECDL tuning AWG, and turn off the piezo driver. Deactivate the sinusoidal waveform to the ECDL on channel 1 of the ECDL bias AWG.
32. Disable the -4 V dc signal to the ECDL, channel 2 on the ECDL bias AWG. Switch the ECDL bias electronics box to “on” to deactivate the ECDL, and shut off the ECDL power supply. Shutdown the wavemeter, both power meters, the second TA’s cooling fan, MCS, and tuning reference power meter. Shut down the ECDL bias and tuning AWG’s.
33. Shut off the MCS box, which should produce an audible tone on the laptop as it loses GPIB signal to the MCS.
34. Switch off the instrument cart power strip. Close LabVIEW and all programs on the laptop and shut it down.
35. Carefully replace the tapered amplifier covers after the amplifier have cooled for about ten minutes. BE CAREFUL to not slide the covers fully onto the TA’s, as this may put pressure on internal wires and damage the TA’s, which has happened in the past.
36. Replace the top covering of the experiment to keep dust off while it is not in use.

APPENDIX D  
LIST OF ACRONYMS

|       |                                                         |
|-------|---------------------------------------------------------|
| AERI  | Atmospheric Emitted Radiance Interferometer             |
| AIRS  | Atmospheric Infrared Sounder                            |
| APD   | Avalanche Photodiode                                    |
| ASE   | Amplified Spontaneous Emission                          |
| AOM   | Acousto-optic Modulator                                 |
| AWG   | Arbitrary Waveform Generator                            |
| CDRH  | Center for Devices and Radiological Health              |
| CW    | Continuous Wave                                         |
| DC    | Direct Current                                          |
| DIAL  | Differential Absorption Lidar                           |
| ECDL  | External Cavity Diode Laser                             |
| FAA   | Federal Aviation Administration                         |
| FOV   | Field of View                                           |
| GSFC  | Goddard Space Flight Center                             |
| LASER | Light Amplification by Stimulated Emission of Radiation |
| LIDAR | Light Detection and Ranging                             |
| MAML  | Multi-Application Montana Lidar                         |
| MCS   | Multi-channel Scalar                                    |
| MM    | Multi-Mode                                              |

|      |                                               |
|------|-----------------------------------------------|
| MSU  | Montana State University - Bozeman            |
| NA   | Numerical Aperture                            |
| NASA | National Aeronautics and Space Administration |
| NB   | Narrow Band                                   |
| OSA  | Optical Spectrum Analyzer                     |
| PBS  | Polarizing Beam Splitter                      |
| PMT  | Photomultiplier Tube                          |
| PZT  | Piezo-electric Tuner                          |
| SM   | Single-Mode                                   |
| SNR  | Signal-to-Noise Ratio                         |
| TA   | Tapered Amplifier                             |
| TEC  | Thermo-electric Cooler                        |