Mesospheric Dynamics and Ground-layer Optical Turbulence Studies for the Performance of Ground-based Telescopes

by

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Abstract

Modern astronomical instrumentation employs adaptive optics (AO) systems that correct for atmospheric distortion in real time in order to produce sharper images. The design and performance of these systems relies on the knowledge of the atmosphere both at low and high altitude. This thesis investigates the first kilometer of the atmosphere, the ground layer (GL), as well as the sodium layer at \( \sim 92 \) km. Newly-designed lunar scintillometers provide turbulence profiles of the GL, and high spatio-temporally resolved sodium profiles are obtained using a newly-designed lidar system for UBC’s 6-m liquid-mirror.

For ground layer adaptive optics systems, knowledge of the local height- and time-resolved GL turbulence is crucial to link local topography to optical turbulence and has been obtained with the help of three lunar scintillometers deployed in Chile, Hawaii and in the Canadian High Arctic. Results from measurements inside the Canada-France-Hawaii Telescope (CFHT) dome indicate severe degradation of image quality due to a poorly vented dome and thus provide input for dome modifications. The outside median GL seeing was determined to be 0.48\( \pm \)0.01". Initial results from the Arctic show exceptional GL seeing conditions, better than have been found anywhere on Earth although data quantity is limited.

Extremely large telescopes must correct not only for GL turbulence, but also higher atmospheric disturbances in the troposphere. The use of laser guide stars (LGS) increases sky coverage and the field of view, but relies on resonantly excited sodium atoms in
the mesosphere. Upper atmospheric dynamics causes varying sodium density, which produces focus-induced wavefront errors in LGS AO systems. The UBC lidar system was built, and its high-resolution data reveal large spatial variability, strong nightly variations and meteor spikes in sodium density on sub-second time scales. The mean altitude power spectrum has been extended to scales approaching the dissipation limit, and its spectral index of $-1.95\pm0.12$ and normalization of $30\pm20$ m$^2$/Hz determines AO system wavefront errors of 4 nm for a 30-m, and 8 nm for a 42-m telescope per meter mean-altitude variation. Derived mean altitudes, separated by one arcmin, showed rms fluctuations of order 30 m and could cause AO performance degradation.
Preface

The work described in this thesis was made possible by support from several people. My primary contributions have been the detailed design, deployment and operation of the ATP and PTP scintillometers, and the detailed design, construction, installation, testing and operation of the LZT lidar system. I also developed most of the data analysis software, and performed all the analysis.

Chapter 6 uses figures, published in a manuscript co-authored with P. Hickson, R. Carlberg, R. Gagne, R. Racine, M. Schoeck, E. Steinbring and T. Travouillon. T. Pfrommer is a co-author. The identification and design of the research program for this paper were carried out jointly. T. Pfrommer was responsible for the design, construction, installation and repairs of the instrument, as well as for communication with on site staff regarding operations of the instrument. Data analysis and operations software, as well as manuscript preparation, was performed by P. Hickson.

Chapter 8 is a manuscript co-authored with P. Hickson, C. Y. She and J. D. Vance. T. Pfrommer is the primary author. The identification and design of the research program for this paper were carried out jointly. Background research, the data analysis, and the preparation of the manuscript were performed by T. Pfrommer, with comments on revisions provided by all coauthors.

Chapter 9 is a manuscript co-authored with P. Hickson and C. Y. She. T. Pfrommer is the primary author. The identification and design of the research program for this paper were carried out jointly. Background research, the data analysis, and the preparation
of the manuscript were performed by T. Pfrommer and P. Hickson, with comments on revisions provided by all coauthors.

Chapter 10 is a manuscript co-authored with P. Hickson. T. Pfrommer is the primary author. The identification and design of the research program for this paper were carried out jointly. Background research, the data analysis, and the preparation of the manuscript were performed by T. Pfrommer, the mathematical derivation as well as comments on revisions were provided by P. Hickson.
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# List of Abbreviations

Acronyms, used in this thesis.

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<thead>
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>alternating current</td>
</tr>
<tr>
<td>ADC</td>
<td>analog-digital converter</td>
</tr>
<tr>
<td>ALMA</td>
<td>Atacama Large Millimeter Array</td>
</tr>
<tr>
<td>ALPACA</td>
<td>Advanced Liquid-mirror Probe for Astrophysics, Cosmology and Asteroids</td>
</tr>
<tr>
<td>AO</td>
<td>adaptive optics</td>
</tr>
<tr>
<td>ATP</td>
<td>Arctic Turbulence Profiler</td>
</tr>
<tr>
<td>BCKDF</td>
<td>British Columbia Knowledge Development Fund</td>
</tr>
<tr>
<td>CANDAC</td>
<td>Canadian Network of the Detection of Atmospheric Change</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CFD</td>
<td>constant fraction discriminator</td>
</tr>
<tr>
<td>CFHT</td>
<td>Canada France Hawaii Telescope</td>
</tr>
<tr>
<td>CFI</td>
<td>Canada Foundation for Innovation</td>
</tr>
<tr>
<td>CSU</td>
<td>Colorado State University</td>
</tr>
<tr>
<td>CTIO</td>
<td>Cerro Tololo Interamerican Observatory</td>
</tr>
<tr>
<td>CTP</td>
<td>Chilean Turbulence Profiler</td>
</tr>
<tr>
<td>cw</td>
<td>continuous-wave</td>
</tr>
<tr>
<td>D$_2$</td>
<td>sodium transition $^3S_{1/2}$-$^3P_{3/2}$</td>
</tr>
<tr>
<td>DAAD</td>
<td>German Academic Exchange Program</td>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DC</td>
<td>direct current</td>
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<tr>
<td>DFT</td>
<td>diffusive filtering theory</td>
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<tr>
<td>DIMM</td>
<td>differential image motion monitor</td>
</tr>
<tr>
<td>DM</td>
<td>deformable mirror</td>
</tr>
<tr>
<td>DND</td>
<td>Department of National Defense</td>
</tr>
<tr>
<td>EC</td>
<td>Environment Canada</td>
</tr>
<tr>
<td>E-ELT</td>
<td>European Extremely Large Telescope</td>
</tr>
<tr>
<td>ELT</td>
<td>extremely large telescope</td>
</tr>
<tr>
<td>ENVISAT</td>
<td>Environmental Satellite</td>
</tr>
<tr>
<td>FET</td>
<td>field-effect transistor</td>
</tr>
<tr>
<td>FoV</td>
<td>field of view</td>
</tr>
<tr>
<td>FPGA</td>
<td>field-programmable gate array</td>
</tr>
<tr>
<td>FWHM</td>
<td>full width at half maximum</td>
</tr>
<tr>
<td>GCM</td>
<td>General-circulation model</td>
</tr>
<tr>
<td>GL</td>
<td>ground layer</td>
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<tr>
<td>GLAO</td>
<td>ground layer adaptive optics</td>
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<tr>
<td>GOMOS</td>
<td>Global Ozone Monitoring by Occultation of Stars - Spectroscope onboard ENVISAT</td>
</tr>
<tr>
<td>HIA</td>
<td>Herzberg Institute of Astrophysics</td>
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<tr>
<td>ĪMAKA</td>
<td>Imaging from MAuna KeA with an atmosphere-corrected one square degree imager</td>
</tr>
<tr>
<td>ITO</td>
<td>indium tin oxide</td>
</tr>
<tr>
<td>JWST</td>
<td>James Webb Space Telescope</td>
</tr>
<tr>
<td>LDEF</td>
<td>Long Duration Exposure Facility</td>
</tr>
<tr>
<td>LGS</td>
<td>laser guide star</td>
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>LIDAR</td>
<td>laser detection and ranging</td>
</tr>
<tr>
<td>LOLAS</td>
<td>low-layer scintillation detection and ranging</td>
</tr>
<tr>
<td>LuSci</td>
<td>Lunar Scintillometer from A. Tokovinin</td>
</tr>
<tr>
<td>LЗT</td>
<td>Large Zenith Telescope</td>
</tr>
<tr>
<td>MASS</td>
<td>multi-aperture scintillation sensor</td>
</tr>
<tr>
<td>MCMC</td>
<td>Markov Chain Monte Carlo</td>
</tr>
<tr>
<td>MKAM</td>
<td>Mauna Kea Atmospheric Monitor</td>
</tr>
<tr>
<td>MKRF</td>
<td>Malcolm Knapp Research Forest</td>
</tr>
<tr>
<td>MLT</td>
<td>upper mesosphere and lower thermosphere</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer onboard Terra and Aqua satellites</td>
</tr>
<tr>
<td>Na</td>
<td>sodium</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>neodymium : yttrium aluminum garnet</td>
</tr>
<tr>
<td>NFIRAOS</td>
<td>Near Field Infrared Adaptive Optics System</td>
</tr>
<tr>
<td>NGS</td>
<td>natural guide star</td>
</tr>
<tr>
<td>NIR</td>
<td>near-infrared</td>
</tr>
<tr>
<td>NSERC</td>
<td>Natural Sciences and Engineering Research Council of Canada</td>
</tr>
<tr>
<td>ODIN</td>
<td>Swedish satellite to study star formation as well as ozone layer depletion and effects of global warming</td>
</tr>
<tr>
<td>OSIRIS</td>
<td>limb-viewing imager onboard ODIN</td>
</tr>
<tr>
<td>PCSP</td>
<td>Polar Continental Shelf Project</td>
</tr>
<tr>
<td>PEARL</td>
<td>Polar Environmental Atmospheric Research Laboratory</td>
</tr>
<tr>
<td>PMT</td>
<td>photo-multiplier tube</td>
</tr>
<tr>
<td>PSD</td>
<td>power spectral density</td>
</tr>
<tr>
<td>PSF</td>
<td>point spread function</td>
</tr>
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List of Acronyms to be continued on next page
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>PTP</td>
<td>Portable Turbulence Profiler</td>
</tr>
<tr>
<td>RFI</td>
<td>radio-frequency interference</td>
</tr>
<tr>
<td>rms</td>
<td>root mean square</td>
</tr>
<tr>
<td>SBC</td>
<td>single-board computer</td>
</tr>
<tr>
<td>SCIDAR</td>
<td>scintillation detection and ranging</td>
</tr>
<tr>
<td>SED</td>
<td>spectral energy distribution</td>
</tr>
<tr>
<td>SKA</td>
<td>Square Kilometer Array</td>
</tr>
<tr>
<td>SLODAR</td>
<td>slope detection and ranging</td>
</tr>
<tr>
<td>SNR</td>
<td>signal to noise ratio</td>
</tr>
<tr>
<td>SODAR</td>
<td>sound detection and ranging</td>
</tr>
<tr>
<td>SPIE</td>
<td>The International Society for Optical Engineering</td>
</tr>
<tr>
<td>TLP</td>
<td>transient lunar phenomena</td>
</tr>
<tr>
<td>TMT</td>
<td>Thirty Meter Telescope</td>
</tr>
<tr>
<td>U of T</td>
<td>University of Toronto</td>
</tr>
<tr>
<td>UT</td>
<td>Universal Time</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>UV</td>
<td>ultra-violet</td>
</tr>
<tr>
<td>WFE</td>
<td>wavefront error</td>
</tr>
<tr>
<td>WFS</td>
<td>wavefront sensor</td>
</tr>
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### Variables, used in this thesis.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>spectral index of mean altitude power spectrum</td>
</tr>
<tr>
<td>$\tilde{\alpha}$</td>
<td>2D angular distance</td>
</tr>
<tr>
<td>$\beta$</td>
<td>power spectrum normalization in lidar data</td>
</tr>
<tr>
<td>$\beta(\lambda)$</td>
<td>scattering probability</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Photon noise floor in mean altitude power spectrum</td>
</tr>
<tr>
<td>$\eta$</td>
<td>efficiency of receiver and uplink optics</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>seeing</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>permeability in vacuum</td>
</tr>
<tr>
<td>$\varepsilon_d$</td>
<td>specific dissipate rate</td>
</tr>
<tr>
<td>$\varepsilon_e$</td>
<td>specific energy transfer rate</td>
</tr>
<tr>
<td>$\varepsilon_{PTP}$</td>
<td>PTP error estimate</td>
</tr>
<tr>
<td>$\varepsilon_{sys,j}$</td>
<td>systematic error for outside/inside scintillometer data</td>
</tr>
<tr>
<td>$\hat{\varepsilon}_{med,i}$</td>
<td>median seeing error of a single bootstrap run</td>
</tr>
<tr>
<td>$\bar{\varepsilon}_{med}$</td>
<td>mean bootstrap median seeing error</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>inverse length scale in von Karman turbulence</td>
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<tr>
<td>$\tilde{k}$</td>
<td>wavevector</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>scattering wavelength</td>
</tr>
<tr>
<td>$\lambda_0$</td>
<td>vacuum wavelength</td>
</tr>
<tr>
<td>$\nu$</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>$\omega$</td>
<td>angular frequency</td>
</tr>
<tr>
<td>$\phi$</td>
<td>phase of incoming wavefront</td>
</tr>
<tr>
<td>$\delta \phi$</td>
<td>phase shift</td>
</tr>
<tr>
<td>$\Phi_v^{3D}(\kappa)$</td>
<td>3D velocity power spectrum</td>
</tr>
<tr>
<td>$\Phi_N^{3D}$</td>
<td>index-of-refraction fluctuation power spectrum</td>
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List of variables to be continued on next page
<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>$\psi$</td>
<td>complex amplitude of a wave</td>
</tr>
<tr>
<td>$\psi_0(\vec{x})$</td>
<td>complex amplitude at telescope pupil</td>
</tr>
<tr>
<td>$\hat{\rho}$</td>
<td>dimensionless spatial variable in units of m/wavelength</td>
</tr>
<tr>
<td>$\sigma_\phi$</td>
<td>rms wavefront error</td>
</tr>
<tr>
<td>$\tilde{\theta}$</td>
<td>angular distance</td>
</tr>
<tr>
<td>$\vartheta_0$</td>
<td>isoplanatic angle</td>
</tr>
<tr>
<td>$\tau$</td>
<td>time scale</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>atmospheric time constant</td>
</tr>
<tr>
<td>$\nu$</td>
<td>velocity</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>zenith angle</td>
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<tr>
<td>$A$</td>
<td>Proportionality constant (Chapter 2)</td>
</tr>
<tr>
<td>$A(\hat{\theta})$</td>
<td>complex amplitude in image plane</td>
</tr>
<tr>
<td>$A_{tel}$</td>
<td>telescope aperture area</td>
</tr>
<tr>
<td>$B_\chi(\vec{r})$</td>
<td>spatial covariance function of log amplitude</td>
</tr>
<tr>
<td>$B_\varphi(\vec{r})$</td>
<td>phase covariance function</td>
</tr>
<tr>
<td>$B_I$</td>
<td>intensity covariance function</td>
</tr>
<tr>
<td>$B_N(\vec{r})$</td>
<td>index-of-refraction covariance function</td>
</tr>
<tr>
<td>$c$</td>
<td>vacuum speed of light</td>
</tr>
<tr>
<td>$C.A.B$</td>
<td>variables for hyperfine interaction (Chapter 4)</td>
</tr>
<tr>
<td>$C_\psi$</td>
<td>spatial coherence function</td>
</tr>
<tr>
<td>$C_2^\nu$</td>
<td>velocity structure constant</td>
</tr>
<tr>
<td>$C_2^N(h)$</td>
<td>turbulence-strength profile</td>
</tr>
<tr>
<td>$C_{Na}$</td>
<td>sodium column density</td>
</tr>
<tr>
<td>$D$</td>
<td>telescope aperture (Chapter 1)</td>
</tr>
<tr>
<td>$d\chi$</td>
<td>log-amplitude variations</td>
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List of variables to be continued on next page
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>$d\sigma/d\Omega$</td>
<td>differential scattering cross section</td>
</tr>
<tr>
<td>$D_\nu(\vec{r})$</td>
<td>velocity structure function</td>
</tr>
<tr>
<td>$D_\varphi$</td>
<td>phase structure function</td>
</tr>
<tr>
<td>$D_N(\vec{r})$</td>
<td>index-of-refraction structure function</td>
</tr>
<tr>
<td>$dh$</td>
<td>thin atmospheric layer thickness</td>
</tr>
<tr>
<td>$E(\kappa)$</td>
<td>specific energy</td>
</tr>
<tr>
<td>$E_{dip}$</td>
<td>energy eigenvalue of dipole hyperfine interaction</td>
</tr>
<tr>
<td>$E_{HFS}$</td>
<td>energy eigenvalue of hyperfine interaction</td>
</tr>
<tr>
<td>$E_{quad}$</td>
<td>energy eigenvalue of quadrupole hyperfine interaction</td>
</tr>
<tr>
<td>$\vec{f}$</td>
<td>angular frequency</td>
</tr>
<tr>
<td>$f(\lambda)$</td>
<td>spectral distribution of the laser line</td>
</tr>
<tr>
<td>$f_{abs}$</td>
<td>absorption oscillator strength</td>
</tr>
<tr>
<td>$F$</td>
<td>hyperfine interaction quantum number</td>
</tr>
<tr>
<td>$F_\Omega$</td>
<td>filter function finite Moon size and different phases</td>
</tr>
<tr>
<td>$F_D$</td>
<td>filter function for finite detector size</td>
</tr>
<tr>
<td>$F_K$</td>
<td>filter function for diffraction</td>
</tr>
<tr>
<td>$F_L$</td>
<td>filter function for von Karman turbulence</td>
</tr>
<tr>
<td>$\mathcal{F}$</td>
<td>Fourier transform</td>
</tr>
<tr>
<td>$g(\lambda)$</td>
<td>spectral function of the absorption line</td>
</tr>
<tr>
<td>$h_P$</td>
<td>Planck’s constant</td>
</tr>
<tr>
<td>$h$</td>
<td>vertical height in atmosphere</td>
</tr>
<tr>
<td>$I$</td>
<td>nuclear spin quantum number</td>
</tr>
<tr>
<td>$I(\vec{\alpha})$</td>
<td>intensity distribution Airy function (Chapter 1)</td>
</tr>
<tr>
<td>$I_0$</td>
<td>maximum intensity in Airy function</td>
</tr>
<tr>
<td>$I_A$</td>
<td>MASS intensity measurement</td>
</tr>
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List of variables to be continued on next page
List of Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$I_i$</td>
<td>Scintillometer intensity measurement</td>
</tr>
<tr>
<td>$J$</td>
<td>total angular momentum quantum number</td>
</tr>
<tr>
<td>$J(h)$</td>
<td>turbulence integral</td>
</tr>
<tr>
<td>$J_1$</td>
<td>Bessel function of first kind</td>
</tr>
<tr>
<td>$k$</td>
<td>wavenumber</td>
</tr>
<tr>
<td>$K$</td>
<td>simplifier variable in Chapter 2</td>
</tr>
<tr>
<td>$K_{ik}$</td>
<td>scintillometer response function</td>
</tr>
<tr>
<td>$l$</td>
<td>length scale</td>
</tr>
<tr>
<td>$L$</td>
<td>angular momentum quantum number</td>
</tr>
<tr>
<td>$l_0$</td>
<td>characteristic outer length scale in atmosphere</td>
</tr>
<tr>
<td>$l_1$</td>
<td>characteristic inner length scale in atmosphere</td>
</tr>
<tr>
<td>$m$</td>
<td>$C_n^2$-reference height index</td>
</tr>
<tr>
<td>$m_e$</td>
<td>electron mass</td>
</tr>
<tr>
<td>$N$</td>
<td>index-of-refraction fluctuation</td>
</tr>
<tr>
<td>$n(\lambda_0)$</td>
<td>index of refraction</td>
</tr>
<tr>
<td>$n_D$</td>
<td>number of illuminated diodes on scintillometer</td>
</tr>
<tr>
<td>$N_{ph}(\lambda, z)$</td>
<td>number of photons on lidar receiver</td>
</tr>
<tr>
<td>$p$</td>
<td>atmospheric pressure</td>
</tr>
<tr>
<td>$P(M</td>
<td>D)$</td>
</tr>
<tr>
<td>$P_{up}$</td>
<td>uplink laser power</td>
</tr>
<tr>
<td>$P_b(\vec{x})$</td>
<td>window function in pupil plane</td>
</tr>
<tr>
<td>$P_a(\nu)$</td>
<td>mean-altitude power spectrum</td>
</tr>
<tr>
<td>$q$</td>
<td>number of noise events with laser off per unit time</td>
</tr>
<tr>
<td>$q$</td>
<td>elementary charge</td>
</tr>
<tr>
<td>$R$</td>
<td>resolving power</td>
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>( r )</td>
<td>transverse distance</td>
</tr>
<tr>
<td>( \vec{r} )</td>
<td>2D spatial separation in horizontal plane</td>
</tr>
<tr>
<td>( R_{\varphi}(\vec{r}) )</td>
<td>phase autocorrelation function</td>
</tr>
<tr>
<td>( r_0 )</td>
<td>Fried parameter</td>
</tr>
<tr>
<td>( r_F )</td>
<td>Fresnel radius</td>
</tr>
<tr>
<td>( Re )</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>( Ri )</td>
<td>Richardson number</td>
</tr>
<tr>
<td>( S )</td>
<td>spin momentum quantum number</td>
</tr>
<tr>
<td>( s_{AB} )</td>
<td>differential scintillation index</td>
</tr>
<tr>
<td>( T )</td>
<td>atmospheric temperature</td>
</tr>
<tr>
<td>( T^{\text{up,down}} )</td>
<td>atmospheric uplink or downlink transmission</td>
</tr>
<tr>
<td>( t )</td>
<td>time</td>
</tr>
<tr>
<td>( \Delta t )</td>
<td>time of flight</td>
</tr>
<tr>
<td>( u )</td>
<td>velocity</td>
</tr>
<tr>
<td>( u_0 )</td>
<td>characteristic outer velocity scale in atmosphere</td>
</tr>
<tr>
<td>( W_{\chi}(\tilde{f}) )</td>
<td>power spectrum of log amplitude</td>
</tr>
<tr>
<td>( \vec{x} )</td>
<td>2D spatial location in horizontal plane</td>
</tr>
<tr>
<td>( z )</td>
<td>range in atmosphere</td>
</tr>
</tbody>
</table>
Acknowledgements

Foremost, I would like to thank my advisor Dr. Paul Hickson for entrusting me with the challenging and interesting topic of this thesis and for lending me his valuable advice, especially in making research activities feasible. His ideas and our numerous discussions were crucial in shaping the scientific course of this work. Working with him was a pleasure for which I am grateful, particularly for his never-ending patience in helping me by answering all my questions. He was always supportive not only during my work at UBC but also by encouraging me to attend conferences, meetings, summer schools and workshops to start collaborations and communicate with the research community in my field. His constructive comments over the entire period of this work led to a substantial improvement of this thesis not only in its presentation but especially in its content.

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For Anka & Tamina
“If the Theory of making Telescopes could at length be fully brought into Practice, yet there would be certain Bounds beyond which Telescopes could not perform. For the Air through which we look upon the Stars, is in a perpetual Tremor; as may be seen by the tremulous Motion of Shadows cast from high Towers, and by the twinkling of the fixed Stars. But these Stars do not twinkle when viewed through Telescopes which have large apertures. For the Rays of Light which pass through divers parts of the aperture, tremble each of them apart, and by means of their various and sometimes contrary Tremors, fall at one and the same time upon different points in the bottom of the Eye, and their trembling Motions are too quick and confused to be perceived severally. And all these illuminated Points constitute one broad lucid Point, composed of those many trembling Points confusedly and insensibly mixed with one another by very short and swift Tremors, and thereby cause the Star to appear broader than it is, and without any trembling of the whole. Long Telescopes may cause Objects to appear brighter and larger than short ones can do, but they cannot be so formed as to take away that confusion of the Rays which arises from the Tremors of the Atmosphere. The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds.”

(Newton 1730)
Part I

Introduction
Chapter 1

Atmospheric Challenges for Future Astronomical Instrumentation

Since the start of modern astronomy, when optical aids like telescopes were used to help reveal the mysteries of the sky, astronomers and physicists noticed their limitations, imposed by the earth’s atmosphere. The passage in the foreword from Sir Isaac Newton’s book (Opticks, 1730) describes and summarizes this problem nicely. While ground-based telescopes, with larger and larger entrance apertures, are able to collect more light compared with telescopes having smaller primary mirrors, and therefore increase their sensitivity (i.e. the ability to distinguish faint objects from a noisy background), they are not able to resolve objects that are too close together. Their resolution is determined by the atmosphere and its characteristic length scale, and not by the telescope aperture itself. The terminology in astronomy for resolution is “seeing” and is defined as the full width at half maximum (FWHM) of the broadening of a point-like distant source, the width of the point spread function (PSF), which is caused mostly by the atmosphere. Other physical limitations such as a finite entrance aperture or instrumental broadening due to diffraction or optical aberration, don’t play a significant role for aperture sizes much larger than the atmospheric coherence length, which will be defined later and is of order ~10 to 20 cm at visible wavelengths. The PSF is caused by random image
motion due to turbulence-induced index-of-refraction changes in the entire atmosphere. The atmosphere blurs the star. In space, where no atmosphere distorts the incoming wavefronts, diffraction-limited performance determines the resolution, and diffraction theory predicts a lineshape, known as the Airy disk. The definition of resolution in such a diffraction-limited imaging system is usually given as the angular distance of the first Airy minimum from the center:

\[ \varepsilon = 1.22 \frac{\lambda}{D}, \]

with \( \lambda \) being the wavelength of an incoming monochromatic wavefront and \( D \) the telescope’s primary mirror diameter. If we consider an optimal telescope with finite circular primary mirror but no atmosphere, the physics of optics gives a natural resolution limit. An undistorted wavefront from a distant point-like light source enters a finite circular entrance aperture (the Fourier plane) and the theory of Fourier optics describes the natural broadening in the image plane to the shape of an Airy function. This can be described through the physical process of Fraunhofer diffraction (Fourier transform of a circular disk). Thus the resulting intensity distribution \( I(\vec{\alpha}) \) can be written in form of a first order Bessel function \( J_1 \)

\[ I(\vec{\alpha}) = I_0 \left[ \frac{2J_1(\pi D|\vec{\alpha}|/\lambda)}{\pi D|\vec{\alpha}|/\lambda} \right]^2, \]

with \( I_0 \) being the maximum intensity at the line center and \( \vec{\alpha} \) the two-dimensional angular distance from the line center. The angular solution of the first minimum of eq. (1.2) shows, with \( \varepsilon = |\vec{\alpha}|_{\text{min}} \), the result of equation (1.1). The less this object is restricted in frequency space (the larger the primary mirror of a telescope), the more defined the object is in the image plane and the better resolved are objects in apparent close proximity to each other.

If we add an atmosphere, the ideal telescope’s diffraction-limited performance with
Figure 1.1: Wavefront distortion due to atmospheric turbulence cells with different temperatures and hence indexes of refraction. Figure credit: Glen Herriot.

respect to resolution is lost and in place of the Airy function, the PSF describes the broadening of the point-like object and contains mostly atmospheric effects. In order to proceed, we need to identify parameters that describe the atmosphere and its properties. Due to the random behavior of fluctuating quantities in the atmosphere, a statistical approach is necessary. The important parameters in the atmosphere are temperature, pressure and density. They all vary on small spatial scales randomly due to predominant large-scale meteorology. The index of refraction, dependent on these quantities, therefore also varies. For example pockets of hotter air have a smaller index of refraction and light traveling through such a cell is advanced compared to its neighbouring wavefront part, which might happen to travel through colder air and therefore is retarded compared to its surroundings. This behaviour is sketched in Figure 1.1. The optical path lengths of the two rays differ and the wavefront gets distorted. Statistically one can define a length scale over which – on average – the distortion of a wavefront through the entire atmosphere is negligible. If we consider a randomly fluctuating distorted phase \( \varphi(\vec{x}) \) of a wavefront in a horizontal plane with \( \vec{x} \) representing the two-dimensional location in this plane, its distortion can be described through the structure function \( D_{\varphi}(\vec{r}) \), where \( \vec{r} \) is a
distinct separation in the horizontal plane. This function determines the mean square difference between two separated phase parts, and the ensemble average is the integral, taken over all coordinates \( \vec{x} \),

\[
D_\phi(\vec{r}) = \left\langle \left[ \phi(\vec{x} + \vec{r}) - \phi(\vec{x}) \right]^2 \right\rangle .
\]

(1.3)

While space-based telescopes have the ability to resolve close objects in angular separation, they are limited by their collecting area due to weight and space limitations of the rockets that transport them into space. Ground-based telescopes not have this restriction and they have the additional advantage of the possibility to be updated with instruments from the newest technologies while most space-based designs are frozen many years ahead of a prospective launch date, and the onboard technology does therefore not contain the latest improvements. Due to their intensive costs the technology used is mostly well established to reduce the risk of failure, which would usually mean the end of the full space mission, while for ground-based designs a new instrument could be put on the telescope much easier and faster compared to a space mission. These advantages put ground-based astronomy in a valuable position to form synergies with space-based time-limited missions. To date, modern astronomy cannot answer or even pose questions that define this vibrant branch of science that “not merely [...] satisfy idle curiosity but [seek answers] for the benefit of all humankind” (Silva et al., 2007).

Advances in modern telescope instrumentation, especially in the last 20 years, have revealed many answers that address questions about the origin of the universe and the current structure, from planetary systems to the largest scales that can be studied in astronomy. Topics like clumpiness of galaxies and the related question about how they are distributed across the sky, show our limited understanding of the universe, which is mostly confined to what we are able to detect - the baryonic content - about 4% of the total energy content of the universe.
The mysteries about dark matter and dark energy that make up the rest of the universe’s energy content are among the biggest questions to be answered with next-generation telescopes. While there is a general understanding of when the first stars were formed, we have not yet seen light from them, nor have we been able to understand the detailed formation mechanisms of stars and, on larger scales, of galaxies. On small angular scales, the most pressing questions are, whether life exists on other planets and whether there are planetary systems similar to the Solar System. One route to a better understanding is to study the planet formation mechanism, both in detail in our own system and statistically in many planetary systems at different times in their life.

To study all these questions, one needs information about the universe on all scales in many different wavelength regions and each of them imposes other challenges to instrumentation. In modern astronomy, synergies between telescopes with different advantages and disadvantages are needed to reveal the best possible multi-wavelength view of the universe. This leads to the necessity of both space- and ground-based approaches to combine the advantages of both. Specifically this means combining high-resolution imaging in small confined fields from space with wide field imaging from the ground. Additional synergies include wavelength ranges from space that are not accessible from ground due to water absorption for example. On the other side, it is technically not feasible to have very high-resolution spectrometers fly on spacecrafts. These would occupy too much room and are better suited for ground-based observatories.

Exploring this unknown world in order to enhance our understanding about the universe on all scales, extremely large telescopes (ELTs) such as the Thirty Meter Telescope (TMT), led by a consortium from North American and perhaps Asia, as well as the European Extremely Large Telescope (E-ELT) have been proposed. Their purpose is to provide unprecedented data in optical and near-infrared wavelengths in order to complement the multi-wavelength global surveys that will be conducted with the Atacama Large Millimeter Array (ALMA), the James Webb Space Telescope (JWST),
Chapter 1. Atmospheric Challenges for Future Astronomical Instrumentation

the Square Kilometer Array (SKA), as well as Herschel and Planck that will provide data on microwave, infrared and radio wavelengths, from ground as well as from space.

Along with many advantages of a large collecting area for these ground-based next-generation optical telescopes, there are technical difficulties to overcome, which have not yet been encountered for smaller telescope designs. For such telescopes to perform at their best, atmospheric distortions need to be corrected to provide a nearly diffraction limited view of the sky. This can be achieved by the usage of an adaptive optics (AO) system, which will be explained in more detail in Chapter 4. With increasing telescope diameter, the advantage of an AO system increases with $D^4$ due to the increase in light-gathering power (proportional to $D^2$) and the simultaneous decrease in background contamination (proportional to $D^2$) that results from higher resolution. Exposure times of unresolved point-like objects that take 8 hours with a current 8-m class telescope, can therefore be reduced to less than 3 min for the TMT in AO mode in order to achieve the same signal-to-noise ratio (SNR).

An AO system senses the phase distortion introduced by the atmosphere using a wavefront sensor (WFS). Its information is analyzed and appropriate commands to correct wavefront distortions are sent to deformable mirrors (DMs), whose surfaces are changed with actuators to compensate incoming distorted wavefronts with the aim of reducing the wavefront error (WFE) on the detector. Since the atmospheric phase distortion changes on a short timescale $\tau$, typically a few milliseconds, corrections must be made at a rapid rate, like 800 Hz as in the design for the high-order AO system for TMT (Herriot et al. 2006). The required phase information can be derived from light received by the telescope from one or more reference stars located near the science target in the field of interest. However in most cases there are no stars of sufficient brightness available close enough to the object being observed (the “science target”). For this reason, ELT AO systems will use artificial stars, created by illuminating the atmospheric sodium layer, located at $\sim 92 \text{ km}$ height and extended in height by 10 to 20 km, using a laser. These “laser guide
stars” (LGS) are cylinders of illuminated sodium atoms, and when seen from most points in the entrance pupil of the telescope (normally the primary mirror), the LGS appear elongated and is caused by the horizontal separation between the laser launch telescope and the observation point. This reduces the accuracy with which the atmospheric phase distortion can be determined due to the light power being spread over more WFS pixels. Fig. 1.2 illustrates this elongation problem.

**Figure 1.2:** Sodium spot elongation on wavefront sensor (WFS) sub-apertures. With increasing radius, the elongation increases and hence the signal-to-noise per WFS pixel reduces, while sodium variability complicates an accurate measurement of the centroid, from Lardiere et al. (2008).

In addition the sodium layer is located in a region of the sky that experiences strong wind shear and influences due to gravity waves from below and meteoric influx, as well as
solar photons that influence atomic oxygen production as well as electron recombination with sodium ions at the top of the sodium layer (Plane 2003). Such energy input causes the sodium layer to be variable in extent and density on time scales ranging from seasonal changes to milliseconds, and therefore imposes problems in the AO system to accurately determine its centroid on the WFS.

For this reason it is essential to map the temporal behavior of the sodium density profile at high frequencies, close to those of the atmospheric focus fluctuations. At the start of the lidar project, described in this thesis, available published sodium layer data did not provide sufficient time resolution due to limited SNR. High spatio-temporal resolution data of the sodium layer are therefore needed and this is a main topic of this thesis.

Laser light detection and ranging (lidar) systems use short laser pulses, tuned to a specific atomic resonance transition, in this case the sodium D₂-line at 589 nm, and send them into the atmosphere. Distant atoms are excited, mostly at the resonance wavelength and isotropic scattering of photons through spontaneous emission occurs. Those photons, directed in the solid angle of the collecting telescope, are focused and guided to a photon counting device. With high-precision timing of the laser pulse launch and the detection of a backscattered photon, the distance to the respective excited atom can be determined. Receiving many photons results in a photon number density profile, which is, if saturation is ignored and correction for the \( z^2 \) projection-effect is applied, directly proportional to the number density of the scattering atomic species. The \( z^2 \)-effect results from the fact that the solid angle of the telescope decreases with the scattering species being further away. Thus, to accurately display a normalized density profile over the whole sodium layer, this effect has to be taken into account. The basic equation for the range \( z \) determination is hereby

\[
z = \frac{c \cdot \Delta t}{2},
\]

(1.4)
with \( c \) being the speed of light in the medium (here, air) and \( \Delta t \) the time of flight. The key system in the UBC system, which extends the sodium data coverage to higher frequencies, is the large collecting area of the 6-m liquid mirror at the LZT, designed and built by P. Hickson, located in Maple Ridge, 65 km east of Vancouver in the UBC’s Malcolm Knapp Research Forest (MKRF) at a latitude of \( 49.2881^\circ N \) \cite{Hickson2007}. The LZT lidar system is introduced in more detail in Chapter 4.

To contribute additionally to advances in modern astronomy, a second approach was taken as a side project. Many projects, used to answer afore-mentioned questions in modern astronomy, don’t necessarily need the absolute best performance that these new technology telescopes at the frontier can provide. By combining ground-based telescope advantages that are able to easily change to new instruments if new technology becomes available, with calm atmospheric conditions which could provide exceptional ground-based resolution, a telescope with a 1 to 2-m primary mirror will provide significant impact. Provided that the atmosphere is very calm, it would perform almost as well as the Hubble Space Telescope, from the ground, at a fraction of the cost. This motivates the search for locations on Earth that have exceptional atmospheric conditions, clear skies, low precipitation, accessibility and cold environment to reduce the thermal background emission.

Such places may be found in the Arctic and the Antarctic and are recognized as potentially great astronomical sites for observatories, due to their desert character and high altitude location in conjunction with low-altitude inversion layers. Recent atmospheric seeing measurements \cite{Lawrence2004} have shown exceptional seeing conditions; however, a very strong ground layer in the first 100 to 200 m degrades the site in the Antarctic near Dome C to a “good but not exceptional site” \cite{Carlberg2010}.

The Arctic has conditions similar to the Antarctic; it has mountains on Ellesmere
Island in the Canadian High Arctic that extend up to 1600 m above sea level near the Arctic Ocean and therefore are not subject to strong boundary layers. Even with the Arctic vortex not being as stable around the pole as it is in the Antarctic, the Canadian High Arctic extends with this preferred terrain, up to 82°N, very close to the North Pole. Dome C is further away from the South Pole. On these grounds, weather data collection started in 2006 on four selected mountain sites \cite{Steinbring et al. 2010}. After three years of data collection and gaining experience in the harsh Arctic environment, the weather data looked sufficiently promising that, as a next step, seeing measurements were needed. For this purpose, we designed and built an instrument, a lunar scintillometer, that is able to withstand the environment and collect seeing measurements up to heights of \( \sim 1 \text{ km} \), by recording scintillation of moonlight. We have operated a similar instrument since 2007 at the Cerro Tololo Interamerican Observatory (CTIO) in Chile and the experience gained by remotely operating such an instrument, helped in the design process and the operations. In Chapter \ref{ch3} this project is introduced in more detail.

Existing telescopes periodically update instrumentation in order to stay competitive by exploiting the increased sensitivity due to the latest technological advances in detectors and instrumental design. Many are planning to install AO systems. One approach is to add a ground layer AO (GLAO) system, which only corrects for wavefront distortions from the lowest 1 km in the atmosphere. In order to properly design such facilities, a local turbulence profile is necessary. For this reason we are currently making ground-layer turbulence measurements with a third lunar scintillometer at the Canada France Hawaii Telescope (CFHT) on Mauna Kea (Hawaii). The observatory is exploring the idea of equipping the 4-m telescope with a ground-layer adaptive optics system, called ÊMAKA (Imaging from Mauna Kea, with an atmosphere-corrected one-square-degree imager) to obtain a well-corrected \( 1^\circ \) field of view (FoV). As a first step, the dome seeing is being evaluated in order to identify possible ways to reduce its contribution.
The work described in this thesis contributes to next-generation astronomical observatories in two ways. First, by providing high-resolution sodium layer data needed to design AO systems for ELTs and second, by obtaining atmospheric seeing data at exceptional sites for future new observatories and new instrumentation for existing observatories. This work therefore combines synergies between different telescope projects to help achieve the best performance, with the ultimate goal of answering fundamental questions in modern astronomy.
Chapter 2

Introduction to the Theory of Optical Turbulence in the Atmosphere

The goal of this thesis is to contribute to the field of ground layer turbulence site testing as well as high-resolution sodium layer dynamics. Both topics rely on optical turbulence and a detailed introduction sets the path for the following chapters. Atmospheric physics and the mathematical description of relevant atmospheric parameters that describe optical turbulence are therefore presented in this chapter.

2.1 Index of Refraction Fluctuations

Optical turbulence is the random variation in atmospheric density and temperature on different time and length scales, which are coupled through thermodynamic laws to the atmospheric pressure. Such variations cause the index of refraction, a function of temperature and pressure, to vary, which in turn cause the optical path length through turbulent cells to vary. Distortion of a passing wavefront on all length scales that are characteristic of turbulent cells is the result. With the atmospheric time scale of order milliseconds, such distortions have also random time dependence on time scales important for astronomical exposure times that barely touch sub-second levels. Thus, long-exposure
images are a composite of many short-exposure speckle images that result from random optical interference patterns due to distorted wavefronts.

The index of refraction in air is dependent on the vacuum wavelength $\lambda_0$ (in nm) (Ciddor, 1996):

\[
n(\lambda_0) = 1 + \frac{0.05792105}{238.0185 - (1000.0/\lambda_0)^2} + \frac{0.00167917}{57.362 - (1000.0/\lambda_0)^2}.
\]  

(2.1)

The temperature ($T$ in K) and pressure ($p$ in Pa) dependence can be expressed as follows (Bönsch & Potulski, 1998):

\[
n(\lambda_0, p, T) - 1 = \left[\frac{n(\lambda_0) - 1}{93214.6} \cdot 10^{-8} \cdot \left[0.5953 - 0.009876 \cdot (T - 273.15)\right] \cdot p\right] + \frac{1 + 0.003661 \cdot (T - 273.15)}{1 + 0.003661 \cdot (T - 273.15)}
\]  

(2.2)

The dependence on the wavelength in Eqn. (2.1) causes $n(\lambda_0)$ to decrease with increasing wavelength. A temperature change has therefore a stronger effect for shorter wavelengths. Thus light with shorter wavelengths is more strongly distorted for the same temperature change, because the index-of-refraction fluctuations increase. Pressure fluctuations travel with the speed of sound, which is orders of magnitudes faster than atmospheric velocities and hence equalize very quickly. Thus at a given height, pressure can be assumed to be constant and only temperature variations matter for the purpose of optical turbulence. The diffraction limit is also wavelength dependent (Eqn. 1.1) and for longer wavelengths for a given telescope aperture, this limit is reached at lower angular resolution compared to shorter wavelengths. For longer wavelengths, the difference between the theoretical and practical limit is hence smaller for a given atmospheric condition, and in case of AO systems, it becomes easier to achieve high performance while correcting for atmospheric distortion for longer wavelengths, since the performance is measured with respect to the theoretical limit.

As light with wavenumber $k = 2\pi/\lambda$ propagates through the atmosphere, it passes
through many different turbulent cells, all of which have slightly different temperatures and hence different indexes of refraction. As the propagation speed varies for different rays, by the time the light reaches the telescope, it is phase shifted from the mean by

$$\delta \varphi = k \int Ndz,$$  \hspace{1cm} (2.3)

where the integral is taken along the line of sight, and exhibits a random phase error that varies with the two-dimensional position $\vec{r}$ on the telescope aperture. In this equation the deviation $N$ of the index of refraction $n$ from the mean $\langle n \rangle$ is used,

$$N = n - \langle n \rangle,$$ \hspace{1cm} (2.4)

instead of the absolute value $n$, to point out the calculation of a phase shift from the mean.

### 2.2 Atmospheric Parameters that Characterize Optical Turbulence

Because astronomy depends on multi-wavelength data, it is important to characterize the atmosphere for the optical and near-infrared wavelength ranges, across which the atmosphere is, apart from some narrow absorption bands, very transmitting. To take advantage of this fact, the best potential telescope sites on Earth are characterized not only by their local statistical meteorological conditions and cloud coverage, but also in the statistics of the in the following described most important parameters seeing, Fried parameter, atmospheric time constant and isoplanatic angle.
2.2.1 Seeing

The atmosphere’s ability to naturally resolve two nearby objects determines the so-called seeing $\varepsilon$, which can be expressed similarly to Eqn. (1.1) but instead of the telescope diameter in the denominator, this time a much smaller quantity is introduced, the Fried parameter $r_0$, described below. As discussed in Chapter 1, the FWHM of the seeing-limited PSF is used as the definition of seeing, which leads to the following relation:

$$\varepsilon = 0.96 \frac{\lambda}{r_0}. \quad (2.5)$$

Taking the median seeing value from the TMT site-testing campaign on Mauna Kea, 0.75 arcsec (Skidmore et al., 2009), the median Fried parameter at 500 nm is 13 cm and ranges from 7 cm to 22 cm for the worst and best 10% of the nights. Therefore even the largest telescopes do not provide - in natural seeing observations - better resolution than an amateur-class telescope. Of course the light gathering power enables deeper imaging. Eqn. (2.5) describes the FWHM of the PSF of a distant point source, which is observed through the atmosphere with natural seeing. The PSF is the response of an imaging system to a point source and can be thought of as a superposition of Airy disks (speckles), diffracted into slightly different random directions, during long exposures. From the central limit theorem, a randomly-fluctuating quantity approaches a Gaussian distribution, and hence a former point-like distant source appears in the core as a Gaussian distribution on the detector. In reality, the envelope is much more extended, because the single Airy disk speckles contribute more and the central limit theorem does not hold anymore in these outer regions of the envelope of a PSF.
2.2.2 Fried Parameter

The Fried parameter, which is the size-determining factor in the PSF, is expressed as (Roddier, 1981)

\[ r_0 = 0.185 \lambda^{6/5} \cos^{3/5} \zeta \left[ \int_0^\infty C_N^2(h) dh \right]^{-3/5}, \]  

with \( \zeta \) being the zenith angle and \( C_N^2(h) \) the height-dependent refractive index structure constant, describing the turbulent strength. The structure constant is a physical quantity of the atmosphere and it describes the mean square difference of index-of-refraction fluctuations of two points, separated horizontally by 1 m. It thus determines the turbulence strength at any given height. Section 2.2.5 gives a more rigorous derivation of this important quantity of the atmosphere and Eqn. 2.28 provides the definition. As later shown, all important atmospheric parameters can be written in terms of the structure constant \( C_N^2(h) \), and hence its determination is of single most importance during a site characterization for astronomical telescopes. After its mathematical derivation in this chapter, its measurement is introduced in Section 3.

To investigate the Fried parameter and the index of refraction structure function together with their relation to atmospheric turbulence and their effect on the phase \( \phi \) of incoming light in more detail, the following derivation shows their functional dependencies. It follows Max (2008), Fried (1966) and Roddier (1981) and defines the terminology used throughout this thesis.

2.2.3 Correlations in Fluctuating Quantities – Covariance and Structure Functions

Light from a distant point source arrives at the top of the atmosphere as a plane wave having complex amplitude

\[ \psi = e^{i\phi(x)} \text{ with phase } \phi(x) = \vec{k} \cdot \vec{x} - \omega t, \]  

(2.7)
where \( \vec{k} \) is the wave vector, describing the direction of the wave, and its amplitude is \( 2\pi/\lambda \). \( \omega \) describes the angular frequency of the wave. To describe the distortion in the spatial direction \( \vec{r} \), the spatial coherence function

\[
C_\psi = \langle \psi(\vec{x})\psi^*(\vec{x} + \vec{r}) \rangle = \left< e^{i[\phi(\vec{x}) - \phi(\vec{x} + \vec{r})]} \right>
\] (2.8)

is introduced. It describes over what length \( r = |\vec{r}| \) the wave is coherent. Because for the current derivation the phases are of importance, the covariance function \( B_\phi(\vec{r}) = \langle \phi(\vec{x})\phi(\vec{x} + \vec{r}) \rangle \) is introduced, which describes the spatial correlation of the phase. The covariance function can be obtained by calculating the autocorrelation function

\[
R_\phi(\vec{r}) = \left< \phi(\vec{0})\phi(\vec{r}) \right>
\] (2.9)

and subtracting the mean \( \langle \phi \rangle \) from each factor in Eqn. (2.9). Thus for zero means, the autocorrelation function is equal to the covariance function \( R_\phi(\vec{r}) = B_\phi(\vec{r}) \), a fact which will become handy later. The autocorrelation function \( R_\phi(\vec{r}) \) is usually defined as a surface integral over \( \phi(\vec{0})\phi(\vec{r}) \). However, for stationary fields, the integral can be replaced by the ensemble average. In this context, “stationary” means that the statistical properties are not dependent on the coordinate. The covariance function \( B_\phi(\vec{r}) \) is related to the structure function for phase fluctuations, which is the mean square difference of phases at different horizontal locations,

\[
D_\phi(\vec{r}) = \left< |\phi(\vec{x}) - \phi(\vec{x} + \vec{r})|^2 \right>
\] (2.10)

By expanding Eqn. (2.10) and again assuming a stationary field, the structure function relates to the covariance function

\[
D_\phi(\vec{r}) = 2 \left[ B_\phi(\vec{0}) - B_\phi(\vec{r}) \right]
\] (2.11)
To evaluate the structure function $D_\varphi(\vec{r})$, we consider a thin horizontal layer with width $dh$ (still much larger than the spatial coherence scale of index of refraction fluctuations) at height $h$. A wave, traveling vertically through this layer exhibits a phase variation at location $\vec{x}$, as expressed in Eqn. (2.3), of

$$\delta \varphi(\vec{x}) = k \int_{h}^{h+dh} dz N(\vec{x}, z). \quad (2.12)$$

Thus, the covariance (Eqn. 2.11) can be expressed in terms of the index of refraction change $N$

$$B_\varphi(\vec{r}) = k^2 \int_{h}^{h+dh} dz' \int_{h}^{h+dh} dz'' \langle N(\vec{x}, z')N(\vec{x} + \vec{r}, z'') \rangle, \quad (2.13)$$

where, for clarity, the cross product has been evaluated with the assumption of the wave traveling vertically. Changing variables $z = z'' - z'$ leads to

$$B_\varphi(\vec{r}) = k^2 \int_{h}^{h+dh} dz' \int_{h-z'}^{h+dh-z'} dz B_N(\vec{r}, z), \quad (2.14)$$

with

$$B_N(\vec{r}, z) = \langle n(\vec{x}, z')n(\vec{x} + \vec{r}, z' + z) \rangle \quad (2.15)$$

being the three-dimensional covariance function. The integration limits of the second integral in Eqn. 2.13 can be replaced with $-\infty$ and $\infty$, since $dh$ is much larger than the correlation scale for index of refraction fluctuations. With both physical height variables $z'$ and $z''$ ranging from 0 to $\infty$, the integration limits of $z = z'' - z'$ range from $-\infty$ to $\infty$. The phase covariance function is hence expressed as

$$B_\varphi(\vec{r}) = k^2 dh \int_{-\infty}^{\infty} dz B_N(\vec{r}, z) \quad , \quad (2.16)$$
With Eqns [2.11] and [2.16] the phase structure function becomes

$$D_\varphi(\vec{r}) = k^2 dh \int_{-\infty}^{\infty} dz \left[ D_N(\vec{r},z) - D_N(0,z) \right], \quad (2.17)$$

where the three-dimensional index of refraction structure function is defined as

$$D_N(\vec{r},z) = 2 \left[ B_N(\vec{0},0) - B_N(\vec{r},z) \right]. \quad (2.18)$$

In order to proceed, a short introduction to turbulence is given in the next paragraph.

### 2.2.4 Kolmogorov Turbulence

According to Kolmogorov’s theory of turbulence, large eddies with characteristic length and velocity scales $l_0$ and $u_0$, transfer energy to smaller and smaller vortices. This picture is valid in the inertial range, which extends from the outer scale, defined by the largest eddies to the inner scale, where kinetic energy is dissipated into heat by viscous action. The turbulent field is assumed to be homogeneous, isotropic, stationary in time and exhibits large Reynolds numbers. Assuming a flow field with characteristic velocity $u$ and the length scale $l$, the Reynolds number is calculated by $Re = ul/\nu$, were $\nu$ is the kinematic viscosity. This energy cascade was first developed by Richardson (1920) and finished by Kolmogorov (1941) (English translation of the originally published 1941 work). Richardson stated that turbulence can be described by eddies on all scales within the inertial range. Each eddy has a characteristic length $l$, in which the turbulent motion can be considered coherent. Each has a characteristic velocity $u(l)$ and, hence, the timescale is $\tau(l) = l/u(l)$. The rate of specific energy transfer $\varepsilon_e$ scales with $u_0^2 / \tau_0 = u_0^3 / l_0$, valid within the entire energy cascade. In equilibrium, $\varepsilon_e$ is equal to the dissipation rate $\varepsilon_d$, which means, the dissipation rate at the smallest scales is already determined by the
largest eddies at the beginning of the energy cascade:
\[
\varepsilon_d \propto \frac{u_0^3}{l_0} . \tag{2.19}
\]

Interestingly, this is independent of the kinematic viscosity \(\nu\). Dissipation, however, ruling the small-scale motion, is describable by \(\nu\) and \(\varepsilon\). With the inner scale length \(l_i\) being the scale, where dissipation starts, the Kolmogorov scales are given by
\[
l_1 = \left(\frac{\nu^3}{\varepsilon_d}\right)^{\frac{1}{4}} \quad u_i = \left(\nu \varepsilon_d\right)^{\frac{1}{2}} \quad \tau_i = \left(\frac{\nu}{\varepsilon_d}\right)^{\frac{1}{2}} . \tag{2.20}
\]

Going back again to Eqn. (2.19), this proportionality can also be used to derive the 3D power spectrum of a turbulent flow. With the above assumption of isotropy, turbulence only depends on the magnitude \(\kappa \sim 2\pi/l\) of the three-dimensional wavenumber \(\vec{k}\) in the range \(d\kappa\). The specific energy in this range thus scales
\[
E(\kappa)d\kappa \propto u^2 \propto \kappa^{-2/3} , \text{ which leads to } E(\kappa) \propto \kappa^{-5/3} . \tag{2.21}
\]

In all three dimensions, \(d\kappa\) needs to be replaced with \(d^3\kappa = 4\pi \kappa^2 d\kappa\) and thus, the three-dimensional specific energy \(E^{3D}\) scales to
\[
E^{3D}(\vec{k})d^3\kappa \propto \kappa^{-11/3} . \tag{2.22}
\]

Thus, the 3D spectral power spectrum for velocity fluctuations \(\Phi^{3D}_v(\kappa)\) has units \(m^2 \cdot m^3 / s^2\) and a 3D volume element
\[
\Phi^{3D}_v(\vec{k})\kappa^2 \Delta\kappa \propto u^2 \propto \varepsilon^{2/3}l^{2/3} , \tag{2.23}
\]
scales like the specific energy that describes the turbulent motion that is created by the velocity fluctuations:

\[ \Phi_3 (\vec{\kappa}) \propto \kappa^{-11/3} . \] (2.24)

This turbulence power spectrum also applies to temperature fluctuations as these are carried by the velocity and do not alter the dynamics of the flow field. From Eqn. (2.2), the dependence of the index of refraction on temperature leads to

\[ \Phi_N^3 (\vec{\kappa}) \propto \kappa^{-11/3} . \] (2.25)

### 2.2.5 Derivation of Refraction Index Structure Constant \( C_N^2 \)

From Eqn. (2.19) follows, \( \upsilon^2 \propto \varepsilon^{2/3} l_0^{2/3} \), where the length coordinate dependence is separated from the energy dissipation and \( \upsilon \) is a general velocity in the atmosphere. The velocity structure function is defined to be the mean square difference of velocities at different separations \( \vec{r} \),

\[ D_\upsilon (\vec{r}) = \left\langle \left[ \upsilon (\vec{x}) - \upsilon (\vec{x} + \vec{r}) \right]^2 \right\rangle . \] (2.26)

With Eqn. (2.19) Eqn. (2.26) leads to

\[ D_\upsilon (\vec{r}) \propto r^{2/3} \text{ or, with the equality sign } D_\upsilon (\vec{r}) = C_\upsilon^2 |\vec{r}|^{2/3} , \] (2.27)

where \( C_\upsilon^2 \) represents the proportionality constant, also called velocity structure constant. In incompressible fluids, the velocity field, described in the last paragraph, carries fluctuations in density and temperature so that the index of refraction structure function has a similar functional dependence:

\[ D_N (\vec{r}) = \left\langle \left[ N(\vec{x}) - N(\vec{x} + \vec{r}) \right]^2 \right\rangle = C_N^2 |\vec{r}|^{2/3} . \] (2.28)
Similarly to Eqn. [2.28], the three-dimensional refraction index structure function can be written as

\[ D_N(\vec{r}, z) = C_N^2 \left( |\vec{r}|^2 + z^2 \right)^{1/3}, \]

and thus with \(|\vec{r}| = r\) and Eqn. [2.17],

\[ D_\phi(\vec{r}) = k^2 C_N^2 dh \int_{-\infty}^{\infty} dz \left[ (r^2 + z^2)^{\frac{1}{3}} - z^\frac{2}{3} \right], \quad (2.29) \]

where the integrand is symmetric. The integral’s solution is

\[ \int_{-\infty}^{\infty} dz \left[ (r^2 + z^2)^{\frac{1}{3}} - z^\frac{2}{3} \right] = \frac{\sqrt{\pi} \Gamma(-\frac{5}{6})}{2\Gamma(-\frac{1}{3})} r^{5/3} = 2.91438 r^{5/3}, \quad (2.30) \]

and the dependence of the phase structure function on the height-dependent refractive index structure constant, which then needs to be integrated over all thin layers \(dh\) in the atmosphere, gives

\[ D_\phi(\vec{r}) = 2.91438 k^2 r^{5/3} \sec \zeta \int_{0}^{\infty} dh C_N^2(h), \quad (2.31) \]

where the zenith angle \(\zeta\)-dependency has been introduced, taking into account the increased thickness of the thin layer \(dh\) for a tilted pass through the atmosphere.

Power spectral density can be related to the autocorrelation function (or covariance function for fields with zero mean fluctuating quantities) through the Wiener-Khinchin theorem, which states that the power spectral density is the Fourier transform of the autocorrelation function. Applied to turbulence in the atmosphere with the index of refraction power spectrum derived in Eqn. [2.25] and the index of refraction fluctuation covariance function from Eqn. [2.15], where the third component \(z\) is now implemented in the three-dimensional vector \(\vec{r}\), this leads to

\[ B_N(\vec{r}) = \int d^3 \kappa \Phi_N^{3D}(\vec{\kappa}) e^{i \vec{\kappa} \cdot \vec{r}}. \quad (2.32) \]
This integral diverges, but the structure function (Eqn. 2.18) does not:

\[ D_N(\vec{r}) = 2 \int d^3\kappa \Phi_N^3(\vec{k}) \left( 1 - e^{i\vec{k} \cdot \vec{r}} \right) . \]  

(2.33)

The structure function is defined as the mean square difference of index of refraction fluctuations, and hence a real quantity, so that only the real part in Eqn. (2.33) has a physical meaning. Additionally, with \( \vec{k} \) and \( \vec{r} \) not necessarily being aligned, but separated by an angle \( \vartheta \), leads to

\[ \int d^3\kappa \text{Re} \left[ e^{i\vec{k} \cdot \vec{r}} \right] = \int_0^\pi d\vartheta \sin\vartheta \int_0^\infty d\kappa 2\pi\kappa^2 \cos(\vec{k} \cdot \vec{r}) = \int_0^\pi d\vartheta \cos(\kappa r \cos\vartheta) \sin\vartheta = \frac{2\sin(\kappa r)}{\kappa r} , \]

(2.34)

which gives

\[ D_N(\vec{r}) = 8\pi A \int_0^\infty \left[ 1 - \frac{2\sin(\kappa r)}{\kappa r} \right] \kappa^{-5/3} d\kappa = \frac{-12\pi A}{5} \Gamma \left( -\frac{2}{3} \right) r^{2/3} = 4\pi A \Gamma \left( -\frac{5}{3} \right) r^{2/3} , \]

(2.35)

where \( A \) is the proportionality constant for Eqn. (2.25). Comparing Eqn. (2.28) with Eqn. (2.35), the refraction index structure constant can now be written as

\[ C_N^2 = 4\pi A \Gamma \left( -\frac{5}{3} \right) \approx 30.2981A. \]

### 2.2.6 Optical Path Difference in Terms of the Fried Parameter

With this result, we can go back to Eqn. (2.8) and derive a formula for the Fried parameter \( r_0 \). As the phase of an incoming wavefront is randomly fluctuating due to atmospheric turbulence, the following equation holds (Fried 1966):

\[ C_\Psi = \left< e^{i(\Psi(\vec{x}) - \Psi(\vec{x} + \vec{r}))} \right> = e^{-\left< |\Psi(\vec{x}) - \Psi(\vec{x} + \vec{r})|^2 \right>/2} = e^{-D_\Psi(\vec{r})/2} . \]

(2.36)
Chapter 2. Introduction to the Theory of Optical Turbulence in the Atmosphere

The phase structure function $D_\phi(\mathbf{r})$ has been given in Eqn. (2.31). With the spatial (also called mutual) coherence function determined, the final question is how the atmosphere affects the natural resolution of a telescope. To answer this question, the size of the turbulent cells, the Fried parameter $r_0$, is the crucial parameter to be used. The resolving power $R$ of a telescope with circular aperture and diameter $r_0$ without atmosphere is defined by diffraction theory as

$$R \equiv \frac{\pi}{4} \left( \frac{r_0}{\lambda} \right)^2. \quad (2.37)$$

With this definition, the atmospheric effect is simulated such that it creates the same diffraction effect on the final image as would a telescope in space having diameter $r_0$. An image of an astronomical object on a detector can mathematically be written as the convolution of the object irradiance function with the PSF, with the two-dimensional angular distance $\mathbf{\theta}$ on the detector as the dependent variable. Taking the Fourier transform of the convolution results in the multiplication of the Fourier transform of the object irradiance function with the Fourier transform $F[PSF]$ of the PSF, also called the optical transfer function $F[PSF]$. The angular frequency $\mathbf{f}$ is now the dependent variable in units $1/\text{rad}$. Usually the optical transfer function is a combination of aberrations in the imperfect optics of a telescope and the atmospheric influences. However with the above assumptions, diffraction theory can be used to describe the influence of the atmosphere. The resolving power $R$ is the integral over all spatial frequencies of $F[PSF](\mathbf{f})$ in case of the ideal telescope in space with a diameter $r_0$:

$$R = \int_{-\infty}^{\infty} d^2 f \, F[PSF](\mathbf{f}) \equiv \frac{\pi}{4} \left( \frac{r_0}{\lambda} \right)^2. \quad (2.38)$$

To relate atmospheric parameters to the optical transfer function, diffraction theory is used to describe a complex amplitude $A(\mathbf{\theta})$ in the two-dimensional image plane due to a
monochromatic incoming wave with wavelength $\lambda$ with complex amplitude $\psi_0(\vec{x})$ at the
telescopes pupil (index 0 indicates pupil position, while Eqn. 2.8 is given for a general
complex amplitude at the entrance of the atmosphere), simulated with a window function
$P_0(\vec{x})$, which is 1 (for an ideal small telescope) inside the aperture, and 0 otherwise
(Roddier 1981):

$$A(\vec{\theta}) \propto \int_\infty^\infty d\vec{x}\psi_0(\vec{x})P_0(\vec{x})\exp(-2\pi i\vec{\theta} \cdot \vec{x}/\lambda) . \quad (2.39)$$

With a variable change $\vec{\rho} = \vec{x}/\lambda$, Eqn. (2.39) can be written in terms of a Fourier transform
$A(\vec{\theta}) \propto \mathcal{F}[\psi_0(\lambda \vec{\rho})P_0(\lambda \vec{\rho})]$. The PSF is now the irradiance, diffracted by the atmosphere

$$PSF = |A(\vec{\theta})|^2 , \quad (2.40)$$

which can be seen as a power spectral density. Using again the Wiener-Khinchin theorem
we can relate its Fourier transform with the autocorrelation function of $\psi_0(\lambda \vec{\rho})P_0(\lambda \vec{\rho})$,

$$\mathcal{F}[PSF](\vec{f}) \propto \int_\infty^\infty \psi_0(\lambda \vec{\rho})\psi_0^*(\lambda (\vec{\rho} + \vec{f}))P_0(\lambda \vec{\rho})P_0^*(\lambda (\vec{\rho} + \vec{f}))d^2 \rho . \quad (2.41)$$

Comparing Eqn. (2.41) with Eqn. (2.38) shows, that for an ideal telescope in space, the
normalized complex amplitude $\psi_0(\vec{x}) = 1$ and the resolving power is

$$R = \int_\infty^\infty P_0(\lambda \vec{\rho})P_0^*(\lambda (\vec{\rho} + \vec{f}))d^2 \rho = \frac{\pi}{4} \left(\frac{r_0}{\lambda}\right)^2 . \quad (2.42)$$

With the wave passing through the atmosphere, $\psi_0(\vec{x}) \neq 1$, and the spatial average over
$\mathcal{F}[PSF](\vec{f})$ is taken in Eqn. 2.41

$$\langle \mathcal{F}[PSF](\vec{f}) \rangle = C_\psi(\lambda \vec{f}) \cdot R , \quad (2.43)$$
where $C_\psi(\lambda \vec{f})$ is the spatial coherence function, defined in Eqns. 2.8 and 2.36

$$C_\psi(\lambda \vec{f}) = \exp \left[ -\frac{1}{2} \left( 2.914k^2 (|\vec{f}| \lambda)^{5/3} \int_0^\infty dh C_N^2(h) \right) \right] . \quad (2.44)$$

Taking the integral over all positive angular frequencies $|\vec{f}| = f$ with $d^2f$ becoming $2\pi f df$, of Eqn. (2.44) and equating the result with the resolving power Eqn. (2.37) gives, with

$$K = \frac{1}{2} \left( 2.914k^2 (\lambda)^{5/3} \int_0^\infty dh C_N^2(h) \right)$$

$$\int_0^\infty 2\pi \exp[-K\frac{5}{3}] f df = \frac{6\pi}{5} K^{-6/5} \Gamma \left( -\frac{6}{5} \right) = \frac{\pi}{4} \left( \frac{r_0}{\lambda} \right)^2 . \quad (2.45)$$

Thus, $K$ can be expressed in terms of the Fried parameter $r_0$ as

$$K = 3.44 \left( \frac{r_0}{\lambda} \right)^{-5/3} . \quad (2.46)$$

This leads to the expression for the PSF in terms of the Fried parameter:

$$C_\psi(\lambda \vec{f}) = \exp \left[ -3.44 \left( \frac{\lambda f}{r_0} \right)^{5/3} \right] = \exp \left[ -3.44 \left( \frac{r}{r_0} \right)^{5/3} \right] . \quad (2.47)$$

Equating the exponent of Eqn. (2.47) with the exponent of Eqn. (2.44) gives the Fried parameter in terms of the structure constant (compared to Eqn. 2.6):

$$r_0 = \left[ 0.423k^2 \sec \zeta \int dh C_N^2(h) \right]^{-3/5} \propto \lambda^{6/5} (\sec \zeta)^{-3/5} \left[ \int dh C_N^2(h) \right]^{-3/5} . \quad (2.48)$$

We can now express the phase structure function, given in Eqn. 2.31 in terms of the Fried parameter as

$$D_\varphi(\vec{r}) = 6.88 \left( \frac{r}{r_0} \right)^{5/3} . \quad (2.49)$$
The phase structure function gives the mean square phase difference between two points on a wavefront, separated by the transverse distance $r$. If the wavefront can be described in a set of orthogonal and normalized polynomials, like the Zernike polynomials, and integrated over the entire aperture, wavefront errors can be determined for each individual wavefront mode. From Noll (1976) it follows that for a piston-removed, but otherwise uncorrected wavefront, the wavefront error due to turbulence is $\sigma_\phi^2 = 1.0299 \left( \frac{r}{r_0} \right)^{5/3} \text{rad}^2$. Piston-removed wavefront error means a wavefront representation, using a complete orthogonal set of basis functions, where the first term, the offset, is neglected as this error does not account for real wavefront errors in an AO system. Therefore, over a distance, determined by the Fried parameter $r = r_0$, the rms phase error is $\sigma_\phi \approx 1.015 \text{rad}$. Expressed in wavelengths (Roddier, 1981), the rms in optical path difference is

$$\sigma_z = k\sigma_\phi = \frac{1.015}{2\pi} \lambda \left( \frac{r}{r_0} \right)^{5/6}. \quad (2.50)$$

An interesting aside can now be seen. From Eqn. (2.48), $r_0 \propto \lambda^{6/5}$, hence $\sigma_\phi \propto \lambda^{-1}$. From this it follows, for a Kolmogorov atmosphere and to first order, that the optical path rms wavefront error is independent of the wavelength $\lambda$ (Roddier, 1981). Implications of this fact are that in an adaptive optics system, the deformable mirror can correct the optical path difference directly no matter what wavelength band is used in the astronomical application.

### 2.2.7 Atmospheric Time Constant

The next atmospheric parameter to be discussed is the atmospheric time constant $\tau_0$. In Eqn. (2.31) if instead of taking the integral over the entire atmosphere, a thin layer of thickness $dh$ is considered. Its contribution $dD_\phi$ to the atmospheric structure function is

$$dD_\phi(\vec{r}) = 2.914k^2r^{5/3}\sec\zeta C_N^2(h)dh. \quad (2.51)$$
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If the intrinsic dynamical evolution of atmospheric parameters is slow compared to the rate at which such fluctuations are advected by prevailing atmospheric wind conditions such as the height dependent wind velocity \( \psi(h) \), the Taylor frozen flow hypothesis (Taylor, 1938) can be used to transform \( r = \psi(h)t \) in Eqn. (2.51) and derive, after integrating over all layers, a temporal structure function

\[
D_\phi(t) = 2.914k^2 \zeta \int_0^\infty dh C_N^2(h) \psi^{5/3}(h) = \left( \frac{t}{\tau_0} \right)^{5/3}, \quad (2.52)
\]

where \( \tau_0 \) is the atmospheric timescale (Roddier, 1981):

\[
\tau_0 = \left( 2.914k^2 \sec \zeta \int_0^\infty dh C_N^2(h) \psi^{5/3}(h) \right)^{-3/5}. \quad (2.53)
\]

With a 10 m/s average wind, and 15 cm for the Fried parameter, this timescale solves to 15 ms.

2.2.8 Isoplanatic Angle

Up to now we looked at the integrated statistical properties of the atmosphere and did not care from which altitude the largest contribution to optical path differences and fluctuations arose. However, there is a difference whether most of the turbulence is located in the first km of the atmosphere, or at around 10 km, a region of high wind shear due to the jet stream (Schöck et al., 2009). Of course turbulence is present in all layers in the atmosphere, but the first km as well as the tropopause region usually contribute the most to the turbulence integral for observatories on mountain tops. This is discussed in more detail in Chapter 3. To understand the atmospheric effect on the image of a science target one usually senses a bright reference star nearby with a WFS. Light from this reference star passes through different volumes in the atmosphere, compared to the science target, especially for the higher regions in the atmosphere, thus common path is
reduced. The isoplanatic angle $\vartheta_0$ determines the angular radius around a science target, for which the mean square wavefront error, averaged over the aperture, is $1 \text{ rad}^2$ (Hardy 1998). With this definition,

$$\vartheta_0 = \left[2.914k^2(\sec \zeta)^{8/3} \int_0^\infty dh C_N^2(h)h^{5/3}\right]^{-3/5} = 0.314\cos \zeta \left(\frac{r_0}{\bar{h}}\right), \quad (2.54)$$

with

$$\bar{h} \equiv \left(\frac{\int_0^\infty dh hh^{5/3}C_N^2(h)}{\int_0^\infty dh C_N^2(h)}\right)^{3/5}, \quad (2.55)$$

and it can be seen that the isoplanatic angle is weighted by $h^{5/3}C_N^2(h)$. This accounts for the fact that turbulence in higher altitudes has a stronger effect on the isoplanatic angle.

### 2.3 Concluding Remarks

From the above discussion, it becomes clear that the atmospheric parameter that best describes aspects of turbulence and the effect on image quality or telescope performance, is the Fried parameter. It determines the average scale in the atmosphere over which the rms wavefront is distorted by less than 1 rad, equivalent to an rms optical path difference of less than $\frac{1}{6}\lambda$ (Eqn. 2.50). Therefore, diffraction-limited images can be recorded with a telescope having a maximum aperture diameter of $r_0$. Any larger telescope suffers from atmospheric distortion, which if not treated by an AO system, reduces the resolution to seeing-limited performance. With the dependence of $r_0$ on $C_N^2$, it follows that the height-dependent structure constant profile is the single most important quantity to be measured if turbulence in the atmosphere is to be evaluated and all other factors follow from it. If the phase structure function $D_\phi(\hat{r})$ is integrated over the entrance aperture of a telescope and a suitable basis function set for the distorted wavefront is used, the wavefront error that arises from atmospheric turbulence can be estimated and hence an
attempt to correct it can be made by means of AO, introduced in Chapter 4, since the second part of this thesis is dedicated to the improvement of the performance of laser guide star AO systems. First however, high-resolution ground layer site testing, will be discussed.
Chapter 3

Ground Layer Site Testing of Optical Turbulence

3.1 Motivation

Having now reviewed the important atmospheric parameters like the seeing $\varepsilon$ (Eqn. 2.5), Fried parameter $r_0$ (Eqn. 2.48), atmospheric timescale $\tau_0$ (Eqn. 2.53) and the isoplanatic angle $\vartheta_0$ (Eqn. 2.54), it is striking that they all can be determined if the height-dependent $C_N^2(h)$ is known. This structure constant profile defines the turbulence strength throughout the atmosphere. Several models have been suggested over the years (Hufnagel 1974, Valley 1980, Tokovinin & Travouillon 2006), to just note a few. However, as stated by Beckers (1993a), the actual profiles vary from site to site and from time to time, and average profiles can only give a guideline. It is therefore important to characterize each site with respect to the $C_N^2$-profile, and not only once, but over years, in order to understand the long-term changes and fluctuations that could have local, diurnal, seasonal or other causes. The Hufnagel-Valley profile is used by Beckers (1993a) to show the different height-dependent contributions to atmospheric turbulence (Fig. 3.1). Three main peaks are apparent in the left panel, which indicate the ground layer (GL) in the first 500 m, the boundary layer up to several km, and the upper atmosphere layer, due to the tropopause wind shear at an altitude of around 10 km altitude. The ground layer turbulence is a result of wind interacting with obstructions that could cause turbulent
wakes. The planetary boundary layer results from interaction of wind at ground level, where the wind velocity at ground level is zero, while the free stream is subject to prevailing wind conditions, which causes shear, and hence generates eddies. It is obvious that this boundary layer is highly variable and influenced by the local meteorology as well as the more global weather pattern in higher regions. To establish a well-mixed turbulent layer extending to several km, a flat area is needed for the turbulence to develop. Comparing the left (sea level) and right (mountain site) panels in Fig. 3.1, it can be seen that this planetary boundary layer is strongly reduced for mountain sites, extending into the laminar free stream flow. This directs us to high mountains with mean prevailing wind directions from regions with no obstacles, such as the ocean. Past the first mountain ridge, a turbulent wake develops and the atmosphere above mountains further inland will be influenced by turbulent wake from the first ridge. However, the ground layer, influenced by local topography, is still existent, as seen in Fig. 3.1. It contributes a very significant fraction (up to 80%) of the integrated $C_N^2$ (Rajagopal et al. 2008). Thus it is
critical to vertically resolve $C_N^2(h)$ in the first 500 m of the atmosphere to understand better the local effects of the topography on the optical turbulence and hence, the seeing. For new designs of telescopes, such measurements could help to identify the required height of the primary mirror above ground in order to get above the strongest turbulence. For existing observatories this investigation could provide valuable input to the design process of future instrumentation.

3.2 Characterizing $C_N^2$-Profiles – Site Test Instruments

3.2.1 General Site Test Instruments for the first 10 km in the Atmosphere

In the last few decades, instruments have been developed to measure $C_N^2$-profiles on all altitude scales. Their main goal is to predict the performance that a large telescope would deliver at that site. Rather than analyzing images from smaller telescopes, which are subject to tracking inaccuracies if the mounts are not of highest quality, and telescope aberrations, direct measurements of the wavefront fluctuations are preferable. The differential image motion monitor (DIMM) measures fluctuations in wavefront slope using two small sub-apertures in one telescope, separated by a few sub-aperture diameters. Fig. 3.2a shows the optical setup. Differential detection is not sensitive to tracking errors, and therefore much more robust, so two star images are recorded on the same CCD and their relative image motions are used to determine the differential wavefront tilt. The outcome is a transverse and longitudinal variance of image motion that can be directly related to the seeing, i.e., the FWHM of a PSF \cite{SarazinRoddier1990}. Shortcomings of the technique include biases that may occur if turbulence is primarily coming from one layer and from one wind direction. Also optical aberrations in the detecting telescope as well as atmospheric propagation errors transform pure phase distortions – to a small
but detectable degree – into a mix of phase and amplitude distortions \((\text{Tokovinin} \& \text{Kornilov} \ 2007)\). Additionally, local effects from the DIMM-telescope hosting dome might contribute to the integrated seeing measurement, and bias the results \((\text{Tokovinin} \ 2010)\). Nevertheless, the DIMM is the standard measurement device to measure the seeing over the full atmosphere, and seeing measurements are generally repeatable to an accuracy of a few percent \((\text{Schöck et al.} \ 2009)\).

The multi-aperture scintillation sensor (MASS) detects intensity fluctuations of light from a bright star and analyzes spatial correlations of fluctuations over different concentric apertures, as depicted in Fig. 3.2b. According to \(\text{Kornilov et al.} \ (2007)\), the differential scintillation index can be determined from intensity measurements from two different
apertures $I_j$, where $j$ represents apertures $A$ or $B$:

$$
\delta^2_{AB} = \left\langle \left( \frac{\delta I_A}{\langle I_A \rangle} - \frac{\delta I_B}{\langle I_B \rangle} \right)^2 \right\rangle .
$$

(3.1)

A turbulence speckle size, if produced by turbulence $z = 10$ km away from the telescope, is about 10 cm in diameter (Fresnel radius $r_F = \sqrt{\lambda z}$). So by cross-correlating intensity fluctuations from different apertures, information about turbulence ($C_2^N dh$) from different layers of thickness $dh$ can be investigated (Tokovinin & Kornilov, 2007). With 4 aperture rings, the atmospheric turbulence can be separated into 6 different layers, the lowest one starting around 500 m. The shortcoming of the MASS analysis is that it relies on weak perturbation theory, which is not always applicable because scintillation is not always weak. Therefore, a MASS tends to overestimate the strong turbulence layers (Schoeck, 2010, private communication).

How reliable are these seeing monitors? According to Tokovinin & Kornilov (2007), it is of great importance to understand the different error terms and biases. While comparison between two identical instruments on the same site can be calibrated to produce seeing measurements to within a few percent, the question of absolute accuracy is not answered. Different DIMM measurements from different sites could be subject to different biases and therefore inter-comparison cannot be guaranteed to be accurate. In an extensive site survey operating two identical DIMM instruments at the same time from the same location, the TMT team found a relative accuracy of 2% for the DIMM instrument (Skidmore et al., 2009). A useful result from a double measurement with DIMM and MASS from the same location is that subtraction of the MASS seeing from the DIMM seeing will give the integrated ground layer contribution below 500 m. This is not resolved but already gives a hint as to which atmospheric region is responsible for most of the detected seeing.

To measure the turbulence profile in the ground layer at high vertical resolution,
there are not many options. SCIDAR (scintillation detection and ranging) uses the scintillation pattern of a binary star of known separation and produces $C_n^2$-profiles via autocorrelation and an inversion algorithm. SLODAR (slope detection and ranging) uses spatial cross-correlation of wavefront slope measurements of a binary star from a Shack-Hartmann wavefront sensor to determine a $C_n^2$-profile. Neither deliver the required vertical resolution in the ground layer. However, Chun et al. (2009) used a SLODAR and a LOLAS (low-layer scintillation detection and ranging) instrument to measure turbulence profiles on Mauna Kea. The SLODAR measurements determined $C_n^2$ at 8 reference heights in the ground layer with 80 m to 160 m resolution and 2 minutes time resolution. The LOLAS data delivered turbulence information with $\sim$20 m resolution every 5 to 10 minutes. Also, they require meter-class telescopes, so are not suitable for site test campaigns in remote locations. The influence of the surface layer, the first 20 to 40 m above the telescope, are not detected reliably with any of these methods. Information from such devices cannot be used directly as input for AO development due to their low time resolution, however results can be used to characterize and compare different astronomical sites.

One technique that can resolve the turbulence profile of the ground layer below 1 km is sound detection and ranging (SODAR). Initially it was developed to provide three-dimensional wind profiles above a site, especially near airports. From the backscatter of acoustic pulses from the boundaries of turbulent cells it is possible to derive a $C_n^2$-profile. The acoustic backscatter cross-section is directly proportional to temperature inhomogeneities and hence boundaries of turbulent cells that exhibit temperature changes cause changes in acoustic impedance. It is therefore possible to measure the mean square difference of temperature fluctuations through the change of the backscatter signal (Crescenti [1997]). The required $C_n^2$ can be recovered with the help of Eqn. (2.2). After emitting a series of intense, highly directional pulses of length between 50 and 300 ms, sometimes at different frequencies to increase the SNR, the backscatter echoes are
recorded. From the backscatter strength the turbulence strength can be inferred, and from the Doppler shift the wind velocities are derived. If pulses are sent out at preset angles compared to the vertical axis, all three dimensions of the wind velocity vector can be retrieved. The height up to which such an instrument is sensitive depends on the accuracy of the calibration, the receiver sensitivity and the transmitted acoustic power. Sophisticated calibration techniques have proven to give reliable seeing measurements to about 5% accuracy (Travouillon 2006). Issues with the SODARS include elevated power requirements, and the units that are capable of retrieving turbulence profiles up to 1 km are large and heavy, which is a problem for site testing in very remote areas. To achieve adequate SNRs, SODARs require 30 minutes of integration time per profile (Els et al. 2009b). Short-term variations are hence averaged out and only long-term changes of a turbulence profile can be investigated.

One other instrument, capable of measuring turbulence profiles in the first 500 vertical meters in the atmosphere, is a lunar scintillometer. A part of the research in this thesis is based on this instrument, and therefore, the method and theory of analysis, as well as the design of different types of lunar scintillometers, are reviewed in detail.

The principle of a lunar scintillometer is outlined in the following, and a more detailed explanation with schematics and diagrams is given in Section 3.3 (Fig. 3.6). An array of photo diodes, separated by different baselines, is used to record intensity variations of moonlight, integrated over the lunar disk, at a sampling rate of order 1 kHz. Variations in intensity are caused by atmospheric turbulence in the lower km of the atmosphere. Each diode has a slightly different line of sight to the Moon and probes a different atmospheric volume up to a certain height, above which two diodes share a common path. Thus, each diode pair with its unique separation baseline has its own response function defining the sensitivity range. By cross-correlating intensity fluctuations between different diode pairs, a height-resolved measurement of the turbulence strength can be obtained. One of the main advantages of such a device is that it measures dimensionless intensity variations
that are directly related to the $C_n^2$-profile. No calibration of the instrument is needed.

### 3.2.2 The Chilean Turbulence Profiler (CTP)

UBC built a lunar scintillometer, called the *Chilean Turbulence Profiler (CTP)* that was shipped to the Cerro Tololo Interamerican Observatory (CTIO) just after my arrival. Designed and built by P. Hickson and the UBC Physics and Astronomy department machine and electronics shops, it employs 12 diodes located along a 1.5 m aluminum beam. The CTP is mounted on a commercially available Losmandy G-11 mount that can be controlled remotely via serial commands. I travelled to CTIO to help set up the instrument. Site testing started with the CTP in 2007 and to date, 700 nights spread over three years have been obtained. Its semi-autonomous operation is reviewed in Section 5.1.

### 3.2.3 The Arctic Turbulence Profiler (ATP)

Experience gained with remote operations of the CTP enabled us to design and build a more rugged lunar scintillometer, able to survive the harsh environmental conditions in the Arctic during the dark winter months. The instrument is called the *Arctic Turbulence Profiler (ATP)*. Fig. 3.3 shows the installed ATP after light rime-ice accumulation and with the window heating system operating. Rime ice is the build-up of ice layers on the surface due to air-borne ice crystals, carried by wind. These ice sheets can get very voluminous, sometimes reaching 30 cm in thickness (Campell Scientific, 2009, private communication). One of the important design feature, is the absence of any moving parts. Tracking of the Moon is accomplished by the use of multiple diodes in a ring with electronic selection of the appropriate diode. As this instrument was intended to be deployed on a remote mountain site, rime-ice accumulations at the entrance windows were of concern and design measures were undertaken to address this problem. Also, in
Figure 3.3: ATP location on the roof of Polar Environmental Atmosphere Research Laboratory (PEARL) after some rime-ice build ups. The black ring modules, each hosting 8 diodes on the circumference, are clearly visible. The golden anodized spacer tubes are not completely clear of ice, nor are the weather sensors on top of the ATP. The total length of the 8\textquotedbl{} diameter aluminum tube is 2.4 m. Guy wires secure the instrument against storms.
dark winter months, power is an issue, so the electronics needed to be rugged and have minimal power consumption. A schematic of the ATP is shown in Fig. 3.4.

This project started in 2008 and the design, in-house fabrication and electronics development by the UBC Physics and Astronomy department machine and electronics shops were finished within 1.5 years. We were able to ship the instrument in fall 2009 with the aim to get initial data in the winter of 2009/2010. For testing and year-round internet availability, the ATP was set-up on the roof of the Polar Environment Atmospheric Research Laboratory (PEARL), located ~15 km from Eureka, an Environment Canada (EC) research station located at 80°N. This station is manned year round and one technician takes care of about 25 instruments at PEARL, one of which is the ATP. A 2-km-long gravel airstrip is available, which can accommodate even aircraft as large as a Boeing 737 or Hercules transporter in early spring. In winter, flights are made typically
once per month. During the summer months, equipment can be sent on an almost weekly basis, dependent on the schedule of flights from the PCSP (Polar Continental Shelf Project) Station in Resolute or Cambridge Bay, further west. A key advantage of PEARL is that internet is available, with sufficient bandwidth that allows us to directly control the ATP remotely. Power is provided to PEARL via a 15-km power line from Eureka. Hence, this is an ideal location to test the ATP remotely. The design and the initial results from the 2009/2010 winter season are reviewed in Sections 6.1 and 6.2. At the beginning of Section 6.1, I will introduce the site test campaign in the high Arctic, led by E. Steinbring from the Herzberg Institute for Astrophysics (HIA) and R. Carlberg from the University of Toronto (U of T) and place the ATP in context with ongoing and planned Arctic site test campaigns.

### 3.2.4 The Portable Turbulence Profiler (PTP)

Due to our experience with ground layer turbulence detection and ranging with the CTP, we were approached by the Director of the Canada-France Hawaii Telescope (CFHT) in Hawaii about possible measurements of the effect of the telescope dome and its microclimate on seeing. This would require measurements of the seeing from inside the dome and would need to be done during normal telescope operations when the moon is suitably located so that moonlight enters through the slit in the dome. Fig. 3.5 shows the PTP acquiring data inside the CFHT dome, lit by moonlight. At other times, the seeing monitor would be located outside and measure seeing concurrently with the DIMM-MASS monitor for comparison and cross-correlation. With these requirements, the Portable Turbulence Profiler (PTP) that I designed was built by the UBC Physics and Astronomy department machine and electronics shops. One important side aspect is that the detector design was exactly the same as that used in the Arctic (Hickson et al. 2010). Operation of the PTP on Mauna Kea enabled us to test the optical system.
as well as the in-house designed preamplifier under actual conditions and compare the results to the well-established DIMM-MASS data from the Mauna Kea Atmospheric Monitor (MKAM) tower on Mauna Kea. We have been observing with the PTP since December 2009. A log of all data acquisition nights is given in Appendix C in Tab. C.1.

A technician or telescope operator sets up the instrument at the beginning of the night near the DIMM-MASS weather station MKAM tower or, if the astronomical target at CFHT is favorable and moonlight enters the dome, the PTP is set up inside. As the slit moves during observation, the PTP is repositioned accordingly.

After this introduction to the three ground layer seeing monitors that have been deployed at northern and southern mid-latitudes as well as at very high northern latitudes, I will review the principles of a lunar scintillometer as well as the analysis method in Section 3.3 before going into the individual designs and results from each astronomical site in Chapters 5 and 6.
3.3 General Design Aspects of a Lunar Scintillometer

Beginning with detecting scintillation from the Sun in the early 90s (Beckers 1993b, 2001; Hill et al. 2006), the technique has been refined and an analysis technique developed for a lunar scintillometer (Hickson & Lanzetta 2004; Hickson et al. 2009, 2010). The basic principle is to measure the intensity covariance function $B(r)$ via intensity fluctuations over different baselines and relate it directly, with the appropriate response function, to the $C_n^2$-profile. This is done by placing diodes on a linear bar, separated such that each diode pair subtends a different separation distance (baseline). Light from the moon passes through the turbulent atmosphere and phase distortions occur as discussed previously. Such phase distortions create intensity fluctuations (scintillation) at the detector. Due to the overlapping fields of view above a certain height for each diode pair, which depends upon their baseline and orientation, the recorded intensity fluctuations are correlated, because part of the recorded light shares a common path. By calculating the covariances of the mean-subtracted and DC-normalized intensities, the amount of correlation is determined and with many baselines, a turbulence profile can be extracted. This principle is shown in Fig. 3.6. The electrical current, produced by each photodiode due to moonlight, is preamplified. This
DC signal is then recorded either with a high-resolution fast 24 bit analog to digital converter card like we use in the setup for the PTP, or via in-house designed electronics that amplify the AC component like for the ATP and the CTP. The detailed design is described in Section 5.2.2. The DC component is then recorded after every block of AC recording and used to normalize the recorded intensity variations, as outlined in Section 3.4 in Eqn. (3.19). In either case (PTP or ATP), the intensity fluctuations we are interested in are of the order 0.01%, hence in the case of direct DC recording we need to record voltage changes down to µV-precision. A quarter moon produces DC values of about 400 mV, which means we need to resolve 40 µV.

With an instrument capable of recording such high-precision fluctuations it is important to understand the systematic errors. The advantage of a lunar scintillometer and its analysis is that no calibration is required because normalized intensity fluctuations directly relate to a covariance function, which in turn directly enables us to estimate the turbulence profile $C_N^2$. A short introduction of the underlying theory is given in Section 3.4. In the following, possible noise sources that affect a lunar scintillometer are outlined.

As already stated, intensity fluctuations down to the 0.01%-level must be measured, hence all light sources that fluctuate on at least such levels and whose light might find its way into the photo detectors will cause serious data contamination due to optical interference (not to be confused with coherent interference of light). Fig. 3.7 shows a sample data file with a time series of an arbitrary 100 sec of raw intensity data from inside the dome. The RFI spikes are clearly visible. Entrance aperture restrictions will help to decrease this effect and with a tracking device that ensures an almost perpendicular line of sight to the moon, such baffles can be designed to strictly limit the allowed field of view. In case of the PTP, we chose ±3° because a low-cost amateur astronomical mount was chosen for the tracking. This may be changed in the future to a smaller field to reduce stray light, especially during data acquisition inside the CFHT dome. In case of
Figure 3.7: Example of a raw intensity time series for all 8 diodes of the PTP from inside the dome during full moon operation. The noisy-looking data series is the actual signal arising from optical turbulence. A dark signal has a noise amplitude of a few 10s of µV. The slightly different DC-offsets do not affect the analysis because every channel is normalized by its DC value for every minute block of data. The clearly visible spikes are caused by RFI interference.

In the ATP the aperture is quite large as every diode needs to have a direct line of sight to the moon for about 2.3 hour. Sky background contribution even with such a large aperture is less than 10% of the DC value. At the location of the ATP in the Arctic not much data contamination from environmental sources is expected so that the large aperture is justified.

Electrical interference may cause contamination of the diode signals on their way to the acquisition card. In case of the PTP, effort has been taken to reduce this by shielding the diodes with their directly-attached preamplifier board. These units are located inside an enclosed aluminum bar. The electrical ground connection is established via the power connection, which connects each diode unit individually to the diode
power supply. Also, each unit is grounded to the aluminum bar. The signal cables are high quality coaxial cables, wrapped in metallic foil. Nevertheless, we do see a 60 Hz contamination, which we filter out via software. The ATP electronics are all contained within an aluminum enclosure. The aperture windows are coated with a metallic coating (Indium Tin Oxide, ITO) for heating purposes, which shield this opening. The ATP is not located in an environment with high RFI contamination, and hence much less exposed to electrical interference compared to the PTP, which is used in close proximity to a large telescope and dome whose motors cause RFI. Mechanical interference will also cause data contamination as well as sky background variations. Sources from these interferences are

- **Optical Interference**
  1. Moonlight reflections
  2. Shadows due to moving external obstacles such as the CFHT dome shutter for the PTP
  3. Other light sources in proximity to a lunar scintillometer

- **Electrical Interference**
  1. A moving telescope causes electrical spikes in the power system and subsequently in the PTP data. These are suppressed by the PTP power supply but there might still be leakage at a small level.
  2. Other RFI in the telescope dome or outside near the MKAM tower which houses electronic equipment

- **Mechanical Interference**
  1. When the PTP is moved during data acquisition, in case some of the diodes lost the moon due to shadowing
2. Vibrations due to wind buffeting or people walking close by

3. Mount tracking errors, mostly important for the PTP

- Transparency Fluctuations

1. Thin cirrus layers cause intensity variations that are not uniformly transmitted through the atmosphere for each diode on the time scales of milliseconds, and hence photometric nights are necessary

2. Other sky background variations that act on sub-second time scales

Such data contamination is usually readily identified by the analysis code and the one-minute data section is removed. With this list it becomes clear why the amount of useful data may be reduced, compared to the raw data acquisition time. In case of the PTP, which is most severely affected, 20% of data taken outside near the MKAM tower, and 45% of data taken from inside the CFHT dome has been removed (see Section 5.3.2 and column 6 of Tab. C.1 in Appendix C). This rejection rate especially for inside measurements is quite high and we are working to mitigate this by using longer aperture baffles, that should reduce moon light reflections from obstacles inside the dome. An improved electrical shielding is used in the future to decrease RFI interference.

3.4 Theoretical Principles of a Lunar Scintillometer

To extend the theoretical considerations from Chapter 2, where solely phase distortions have been discussed, amplitude fluctuations due to Fresnel diffraction at the detector location, the basic measurement principle, are discussed. This summary is based largely on an unpublished report by P. Hickson (2010).
3.4.1 From Intensity Fluctuations to $C_N^2$

With wavefront phases being retarded or advanced due to optical path fluctuations, individual rays are slightly tilted in random directions, which leads to intensity fluctuations of order $10^{-4}$ with respect to their absolute intensity. With intensity fluctuations being defined to have zero mean (any random Gaussian process can be defined that way), the covariance function is the autocorrelation function and hence the spatial intensity power spectrum can be obtained via Fourier transform of the covariance function. For Kolmogorov turbulence the following index of refraction power spectrum holds (see also Section 2.2.4):

$$\Phi_3^D(\vec{\kappa}) = A\kappa^{-11/3} = \frac{1}{4\pi\Gamma(-5/3)}C_N^2\kappa^{-11/3}.$$  (3.2)

Comparing this equation with Eqn. (2.35)

$$D_N(\vec{r}) = 8\pi A \int_0^\infty \left[1 - \frac{2\sin(\kappa r)}{\kappa r}\right] \kappa^{-5/3} d\kappa = \frac{-12\pi A}{5} \Gamma\left(-\frac{2}{3}\right) r^{2/3} = 4\pi A \Gamma\left(-\frac{5}{3}\right) r^{2/3},$$  (3.3)

where $D_N$ denotes the index of refraction structure function (Roddier, 1981), reveals that the power spectrum proportionality constant $A \approx 0.033 C_N^2$ (from Eqn. 3.2). Following Roddier (1981) or Hickson & Lanzetta (2004), this power spectrum can be transformed into a phase power spectrum by using the transformation from the index of reflection covariance function to the phase covariance function (see Eqn. 2.16). In order to match variables between the covariance function and the power spectrum, we need to transform the dependent variable $\vec{\kappa} = 2\pi \vec{f}$ in the power spectrum from Eqn. (3.2) via

$$W_N^{3D}(\vec{f}) = (2\pi)^3 \Phi_N^{3D}(\vec{\kappa}) .$$  (3.4)
Thus, taking the Fourier transform of Eqn. (2.16) gives the power spectrum $dW^3D(\vec{f})$, if the turbulence is confined to a thin layer $dh$,

\[
dW^3D(\vec{f}) = k^2 dh 8\pi^3 \Phi^3D(2\pi \vec{f}) = k^2 dh 8\pi^3 0.033 C^2_N(h)(2\pi f)^{-11/3} = 0.00969 k^2 f^{-11/3} C^2_N(h) dh . \quad (3.5)
\]

For the effect of turbulence on the power spectrum throughout the atmosphere, we need to integrate Eqn. (3.5) over the atmosphere. However first we need to apply Fresnel diffraction to radiation with complex amplitude, whose real part is the log amplitude $\chi$, in order to determine how phase variations that occur in an atmospheric layer with width $dh$ at height $h = z\cos\zeta$ translate to log amplitude variations $d\chi$ in the detector plane at $h = 0$ m. $\zeta$ is the zenith angle and $z$ the range from the detector through the line of sight to the layer $dh$. Roddier (1981) demonstrated this and found, with $\vec{x}$ being the 2D coordinate in the perpendicular plane to the line of sight,

\[
d\chi(\vec{x}, z = 0) = \delta \phi(\vec{x}, z) * \frac{1}{\lambda z} \cos\left(\frac{\lambda z}{\lambda \zeta}\right) . \quad (3.6)
\]

This equation made use of the Fresnel approximation. The $*$-sign describes a convolution.

The Wiener-Khilchin theorem relates the covariance to the spatial power spectrum. The spatial covariance function of the log amplitude $B_{\chi}(\vec{r})$ is defined as

\[
B_{\chi}(\vec{r}) = \langle \chi(\vec{x})\chi(\vec{x} - \vec{r}) \rangle . \quad (3.7)
\]

$B_{\chi}(\vec{r})$ is evaluated at $z = 0$ and thus, the power spectra of the log amplitude fluctuations is

\[
W_{\chi}(\vec{f}) = \int B_{\chi}(\vec{r}) \exp^{-2\pi i \vec{f} \cdot \vec{r}} d^2r . \quad (3.8)
\]
Eqn. 3.7 holds for any fluctuating quantity, thus also for $d\chi$. In addition, the covariance function can be viewed as correlation product. Cross correlations (indicated with the ⋆-sign) are however convolutions (indicated with the ∗-sign) with one of the factors being complex conjugate (indicated with superscript ∗) and a negative argument:

$$B_{\chi}(\vec{r}) = \chi^* \ast \chi = [\chi^*(-\vec{x})]^* \ast \chi \quad .$$

(3.9)

Thus, substituting Eqn. (3.6) in Eqn. (3.7) gives

$$B_{\chi}(\vec{r}) = \left[ \delta \phi(\vec{x},z) \ast \frac{1}{\lambda z} \cos \left( i \pi \frac{x^2}{\lambda z} \right) \right] \ast \left[ \delta \phi(\vec{x},z) \ast \frac{1}{\lambda z} \cos \left( i \pi \frac{x^2}{\lambda z} \right) \right] \quad .$$

(3.10)

Taking the Fourier transform $\mathcal{F}$ of Eqn. (3.10) and applying Eqn. (3.9) gives

$$\mathcal{F} [B_{\chi}(\vec{r})] = \mathcal{F} \left[ \delta \phi(\vec{x},z) \ast \frac{1}{\lambda z} \cos \left( \pi \frac{x^2}{\lambda z} \right) \right]^* \cdot \mathcal{F} \left[ \delta \phi(\vec{x},z) \ast \frac{1}{\lambda z} \cos \left( \pi \frac{x^2}{\lambda z} \right) \right] \quad .$$

(3.11)

This can be simplified to

$$\mathcal{F} [B_{\chi}(\vec{r})] = \langle \phi(\vec{x}) \phi(\vec{x} - \vec{r}) \rangle \cdot \frac{1}{(\lambda z)^2} \left| \mathcal{F} \left[ \cos \left( \pi \frac{x^2}{\lambda z} \right) \right] \right|^2 \quad .$$

(3.12)

Now all what is left, is to Fourier transform the cosine, which can be done with the help of the Fourier transform of a Gaussian function with complex argument. Using Cauchy’s ring integral theorem in the complex plane leads to

$$\mathcal{F} \left[ \cos \left( \pi \frac{x^2}{\lambda z} \right) \right] = -\lambda z \sin \left( \pi \lambda z |\vec{f}|^2 \right) \quad .$$

(3.13)
Thus we have the solution for the power spectrum of log amplitude fluctuations on the ground resulting from phase fluctuations in a thin layer at range \( z \) from the detector:

\[
\delta W_{\chi}(\vec{f}) = \mathcal{F} \left[ B_{\chi}(\vec{r}) \right] = \langle \phi(\vec{x}) \phi(\vec{x} - \vec{r}) \rangle \cdot \sin^2 \left( \pi \lambda z |\vec{f}|^2 \right)
\]

(3.14)

or, with the correlation of phase fluctuations expanded:

\[
\delta W_{\chi}(\vec{f}) = \int \langle \phi(\vec{x},z) \phi(\vec{x} - \vec{r},z) \rangle \exp^{-2i\pi\vec{r} \cdot \vec{f}} d^2 r \cdot \sin^2 \left( \pi \lambda z |\vec{f}|^2 \right)
\]

(3.15)

If Kolmogorov turbulence is assumed, the log amplitude power spectrum for an incoming wave is given with \( |\vec{f}| = f \) [Roddier 1981]:

\[
W_{\chi}^{3D}(\vec{f}) = 0.38 \lambda^{-2} f^{-11/3} \int_0^\infty dh C_N^2(h) \sin^2(\pi \lambda h \sec \zeta f^2)
\]

(3.16)

with the zenith-angle \( \zeta \) is introduced to account for off-zenith observations. Here, integration over all ranges \( z \) has been performed to get the total effect of the ground layer atmosphere instead of the single layer \( dh \). Using the Fourier transform of Eqn. (3.8), introducing filter functions for the extended moon source \( F_{\Omega} \) and the finite detector size \( F_D \) and substituting back from \( \vec{f} \) to \( \vec{\kappa} \), the intensity covariance function can now be written as

\[
B_{\chi}(\vec{r}) = 2 \pi \int_0^\infty z^2 dz \int_0^\infty \kappa^4 W_{\chi}^{3D}(\vec{\kappa},z) F_k(\kappa,z) F_{\Omega}(z\vec{\kappa}) F_D(\vec{\kappa}) \exp^{i\vec{\kappa} \cdot \vec{r}} d^2 \kappa
\]

(3.17)

where the \( \sin^2 \) is now hidden in a filter function \( F_k = \text{sinc}^2 [z\kappa^2/(2\pi k)] \). This quantifies the high-frequency attenuation of the curvature power spectrum by diffraction. It also eliminates the explicit wavelength dependency of the covariance function. The other filter functions are briefly described in Section 3.5.
3.4.2 Basic Theory of Measurement

From this derivation follows that intensity fluctuations due to turbulence can be used to determine the $C_N^2$-profile, from which all atmospheric parameters follow to characterize optical turbulence for astronomical observations. Via an inverse Fourier transform, the power spectrum can be used to calculate the intensity covariance function ($B_I = 4B_\chi$, because it is the intensity covariance), which is the equation to be used in lunar scintillometer measurements:

$$B_{I,ik} = \int_0^\infty dh C_N^2(h) h \sec \zeta K_{ik}(\vec{r}_{ik},h). \quad (3.18)$$

The response function $K_{ik}(\vec{r}_{ik},h)$ will be discussed in detail below. It is a function of baseline $\vec{r}_{ik} = \vec{r}_i - \vec{r}_k$, and includes the turbulence spectrum as well as a model of the moon intensity distribution at the time of observation.

The intensity covariance function $B_{I,ik}$ for two diodes $i,k$ is:

$$B_{I,ik} = \left\langle \left[ \frac{I_i}{\langle I_i \rangle} - 1 \right] \left[ \frac{I_k}{\langle I_k \rangle} - 1 \right] \right\rangle. \quad (3.19)$$

$I_i = I(\vec{r}_i)$ represents the intensity recorded by diode $i$ and the inner ensemble average is the time average intensity over a 1 min time interval. This interval choice is justified because it is long compared to the atmospheric coherence time. Thus a $C_N^2$-profile is determined every minute and therefore a seeing time series over the night results in these time steps. The approach to estimate the $C_N^2$-profile is outlined after the response function has been introduced in more detail. It is the product of several filter functions that can be determined prior to observing, as they don’t depend on the data, but only on the response of the instrument to the current moon condition, a chosen turbulence model and instrumental design parameters such as baseline separations and sensitive photo detector area.
3.5 Filter Functions

Several filter functions, summarized in the response function $K_{ik}(\mathbf{r}_ik,z)$ (Eqn. 3.18) must be computed for the lunar scintillometer analysis as shown in Eqn. (3.17). In the analysis, written by P. Hickson, the von Karman power spectrum, which will be introduced in the next section, instead of the Kolmogorov power spectrum is used and hence the outer scale $l_0$ included. Also the moon phase information is introduced. In order to efficiently calculate the data, a look-up table of the response function $K_{ik}(\mathbf{r}_ik,z)$ was created with 3 different outer scales, moon intensity values for every degree in moon phase, and for every baseline throughout the ground layer up to 1 km height. Fig. 3.8 shows an example of the response for a full moon and an outer scale of $l_0 = 20$ m. From previous considerations,

![Figure 3.8: Response function for the PTP with its 28 baselines for the full moon with an outer scale of $l_0 = 20$ m. The individual curves represent the covariance produced on a given baseline by a unit impulse of $C_N^2$ at the specified range. The first, highest curve is the 0-baseline (variance). The small negative values at the lower end of each diode pair indicate anticorrelations and arise from the finite detector size. The fall-off above 500 m to 1 km shows the averaging effect of scintillations with the beam diameter approaching the outer scale.](image-url)
the response function can be written as

$$K_{ik}(\vec{r}_{ik},z) = \frac{\Gamma\left(\frac{8}{3}\right)\sin\left(\frac{\pi}{3}\right)}{2\pi} \varepsilon^2 \int_0^\infty \kappa^{1/3} F_L(\kappa) F_k(\kappa,z) F_\Omega(z\kappa) F_D(\kappa) \exp[i\vec{k} \cdot \vec{r}] d^2\kappa \quad . \quad (3.20)$$

Eqn. (3.20) now shows that all response function contributions should be calculated in the frequency domain, multiplied together and then Fourier transformed. The resulting kernel $K$ is the factor in Eqn. (3.18). And with the measurements forming the covariance function $B$ in Eqn. (3.19), $C_N^2$-profiles are obtained, as per Eqn. (3.18). To summarize, $F_k$ represents the von Karman correction to the Kolmogorov turbulence model, $F_L$ includes diffraction effects, $F_\Omega$ takes the extended moon disk and the related finite beam area into account, and $F_D$ deals with the spatial filtering due to a finite detector size.

### 3.5.1 von Karman Modification of Kolmogorov Turbulence

The von Karman turbulence model is a modified Kolmogorov spectrum that takes the outer scale into account,

$$W(\kappa,z) = \frac{\Gamma\left(\frac{8}{3}\right)\sin(\pi/3)}{4\pi^2} C_N^2(z) \left(\kappa^2 + \kappa_0^2\right)^{-11/6} \quad , \quad (3.21)$$

with $\kappa_0 = 2\pi/l_0$ representing the wave number of the outer scale $l_0$. As introduced in Section 2.2.4, Kolmogorov’s theory of energy cascade is only valid within the inertial range. This is however not accounted for in the initial equations. von Karman therefore introduced the outer scale to mathematically use the turbulence model for all larger length scales (Chesnokov & Skipetrov 1997). Eqn. (3.21) can now be written as

$$W(\kappa,z) = \frac{\Gamma\left(\frac{8}{3}\right)\sin(\pi/3)}{4\pi^2} C_N^2(z) \kappa^{-11/3} F_L(\kappa) \quad , \quad (3.22)$$
where
\[ F_L(\kappa) = \left[ 1 + \frac{\kappa^2}{\kappa_0^2} \right]^{-11/6}. \]  (3.23)

### 3.5.2 Lunar Model for Relative Intensity Response

To take into account the different intensity levels for the varying lunar phase \( \alpha \) over the course of one lunar cycle, the Lommel-Seeliger law [Lindegren, 1977] is employed,

\[ I(\mu, \mu_0, \alpha) = \frac{2I_0 f(\alpha) \mu_0}{\mu + \mu_0}, \]  (3.24)

with \( \mu_0 \) being the direction cosine of the incident radiation, and \( \mu = \cos \theta \) being the direction cosine of the scattered radiation with respect to the normal to the lunar surface. \( I_0 \) is the full moon intensity (i.e. \( \mu = \mu_0 = 1 \)). \( f(\alpha) \) is the scattering function, normalized to unity at full moon \((\alpha = 0)\). Transforming Eqn. (3.24) into spherical Moon-centered coordinates whose polar axis is perpendicular to the plane containing Sun, Moon and observer and the azimuth angle \( \Phi = 0 \) points to the observer, one gets

\[ I(\Phi, \alpha) = \frac{2I_0 f(\alpha)}{1 + (\cos \Phi / \cos (\Phi - \alpha))}, \]  (3.25)

Thus with the intensity calculated, the response function due to the finite beam size can be given, with \( \theta \) being the angular coordinate on the moon:

\[ F_\Omega(\vec{k}_z) = \left| \int I(\theta) \exp(-i\vec{k}_z \vec{\theta}) \, d\Omega \right|^2. \]  (3.26)

### 3.6 Analysis Method

To summarize, intensity fluctuations are measured between pairs of diodes, separated by different distances and the intensity covariance function is calculated. The measured covariance should match the prediction of Eqn. (3.18) if the correct \( C_N^2 \)-profile is chosen.
and the respective response function $K_{ik}(\vec{r}_{ik}, z)$ for the time of observation is taken. A covariance value is built every minute of data for every baseline. The mean for every minute is used to calculate the DC value used to normalize the data (the denominator in Eqn. 3.19).

In a sophisticated analysis approach developed by P. Hickson, the Bayesian posterior probability is calculated for a chosen profile and parameters are adjusted to give the most probable model for the $C^2_N$-profile, defined by maximizing the negative logarithm of the posterior probability [Hickson et al., 2009]. As the response function is a function of distance to an atmospheric layer, each chosen response function contributes a part to the total ground layer turbulence profile. In order not to rely on any prior $C^2_N$-profile, that might not be applicable to the current atmospheric conditions, $C^2_N$ is defined by $m = 7$ independent parameters, each corresponding to $\ln(C^2_N)$ at a specific height, determined to provide a reasonable representation of the profile across the ground layer by taking into account the instrument response functions. Values for the 7 parameters are drawn from a normal distribution during the process of the Markov Chain Monte Carlo (MCMC) optimization. The prior probability is computed assuming that the true values have a normal distribution with mean and variance described by the prior model. The insensitivity of the lunar scintillometer to high-altitude turbulence gives an additional constraint such that the last $C^2_N$ value is set to a very small value, close to zero.

The posterior probability $P(M|D)$ of the model $M$ given the data $D$ to be maximized, calculates as follows

$$P(M|D) \propto P(M)P(D|M),$$

where $P(M)$ is the prior probability of the model and the probability of the data given the model $P(D|M)$ is the likelihood function. To calculate the likelihood function, the covariance matrix of the data, that gives the temporal cross correlations between different diode pairs is used. This is necessary because the same measurement from one diode is
used for many different baselines, and hence the covariances $B_{ij}$ are correlated. So the joint probability density function for non-independent variables is to be used (the upper index $^T$ represents the transposed matrix)

$$P(D|M) = \exp \left\{ -\frac{1}{2} \sum_{a,b} (B^D_a - B^M_a)^T C_{ab}^{-1} (B^D_b - B^M_b) \right\}^{1/2}, \quad (3.28)$$

with $C_{ab}$ being the covariance matrix containing the cross correlation between the different data pairs \cite{Tokovinin et al. 2010}

$$C_{ab} \equiv \text{Cov}(B_{ij} B_{kl}) = \frac{1}{T} \int_{-T/2}^{T/2} d\tau \left[ B_{ik}(\tau)B_{jl}(\tau) + B_{il}(\tau)B_{jk}(\tau) \right] , \quad (3.29)$$

where $a$ represents baselines between diodes $i$ and $k$, and $b$ indicates baselines between diodes $k$ and $l$. The prior probability of the model parameters given a prior model is

$$P(M) = \exp \left\{ -\sum_{m=1}^{7} (M_m - p_m)^2 \right\} , \quad (3.30)$$

where the summation extends over the 7 model parameter. Setting the prior contribution up as given in Eqn. (3.30) ensures the possible $C_2^N$ values for each reference height give a sensible profile (e.g. non-negative, because $C_2^N$ is defined as the mean-square difference of index of refraction fluctuations over a one meter separation). In this approach the Cerro Pachon model \cite{Tokovinin & Travouillon 2006} is used as a starting point, but as it turns out, the particular choice of prior is not of great importance and the fit of the model to the data is primarily constrained by the likelihood function (Eqn. 3.28). To verify this, A. Tokovinin and P. Hickson observed with two different lunar scintillometers at CTIO (LuSci and the CTP) side by side. While A.Tokovinin uses his own analysis method, based on a least squares approach (which implicitly assumes a uniform prior) the CTP data was analyzed with the outlined approach and very good agreement was
found (Tokovinin, 2010), as seen in Fig. 3.9. Interpolating between the reference heights gives $C_N^2$ values at other heights. The turbulence integral is defined by

$$J(h) = \int_h^\infty dx C_N^2(x).$$

(3.31)

This gives the contribution from turbulence at height $h$ up to the outer range of the sensitivity of the lunar scintillometer at $\sim 1$ km. Using Eqns. (2.5) and (2.6), a seeing estimate is obtained for a telescope at any height. An example of the result of a lunar scintillometer can be seen in Fig. 3.10, where the ground layer turbulence is mapped as a time series of $C_N^2$-profiles, and the corresponding seeing values above the indicated heights.
are shown below. At the beginning of this specific night, a relatively strong boundary

![Time variations of CN² profiles for the Ground Layer (GL) on Mauna Kea outside CFHT dome on 2010-08-230](image1)

![GL Seeing (FWHM) in arcsec above indicated height](image2)

**Figure 3.10:** Example of scintillometer result. The ground layer turbulence map shows many interesting features and the underlying seeing plots directly give the information about what resolution performance a telescope at the indicated height, pointing at Zenith at 500 nm, would be able to achieve.

layer in the first 10 to 20 meters was observed. At around 6 UT, turbulence in the 100 m to 300 m region starts to gain strength and stays there for about an hour. The effect on the seeing is evident and bad conditions in the ground layer are derived. After the atmosphere calms down, 3 hours of weak ground layer makes for excellent conditions, while a weak increase in turbulent strength is still evident around 20 m height. Between 10:30 UT and 11 UT another turbulent content is visible in the 100 m to 300 m region. This contamination disappears from the line of sight to the Moon shortly after and beyond 11:30 UT the distinct layer around 20 m gains in strength and extends to the ground after 12:30 UT, making for worse seeing conditions. This now strong boundary
layer in the first 10 to 20 m gains more and more strength until the Sun rises, and the last 2 hours of observing are affected by this strong layer. Over all, this night had a median GL seeing of 0.44" above 6 m, while the DIMM instrument, located right beside the PTP on a 6 m tower, measured 0.45". Besides the obvious uncertainties of local effects with the two instruments pointing to different positions in the sky, this shows that not much free atmospheric turbulence was around during that night and most of the seeing was created in the first 100 to 300 m. It is hence of great importance to resolve this layer to understand local topography and its effect on optical turbulence. This can help to locate future telescopes as well as help to design next-generation AO systems like İMAKA for CFHT.
Chapter 4

Lidar Measurements of Mesospheric Dynamics for Adaptive Optics Design

4.1 Introduction to Adaptive Optics and the Guide Star Problem

Having so far reviewed theoretical background for atmospheric turbulence in the lower atmosphere, the focus changes now to the highest layers of the atmosphere, the upper mesosphere and lower thermosphere (MLT). A region below the ionosphere, extending from 80 to 100 km, contains, besides other metals, neutral sodium in relatively high abundance. That element is deposited by micrometeorites that enter the Earth’s atmosphere and ablate in this region (Plane 2003). Drifting downward to lower regions of the atmosphere with increasing air density, sodium combines with oxygen to form sodium hydroxyl and other molecules. It is then no longer detectable as neutral sodium. This recombination occurs around 75 km to 80 km and is usually defined with a sharper boundary than the upper range limit, which points to a fast reaction rate when the air density reaches a critical limit (Plane 2003). Sodium atoms, resonantly excited by the powerful lasers of an LGS AO system, emit photons isotropically and some are captured
by the telescope to sense the wavefront error produced by turbulence in the lowest 10 km of atmosphere, (see Chapter 1). The TMT will use multiple LGSs, deployed throughout the field of view of the telescope, each with its own WFS. It is therefore important to understand short-time-scale structure changes in the sodium layer to investigate the impact of each LGS probing a different structure, even on spatial scales of tens of meters at 92 km height. In addition to its high abundance in the MLT region, sodium also has a relatively large backscatter cross-section and thus provides the largest return flux of all metals in this layer.

In a typical Shack-Hartmann wavefront sensor, the pupil is divided into subapertures and the light from each subaperture is brought to a focus on a CCD detector by a lenslet array. Thus, for each subaperture, a small image of the LGS is the result. The position of this elongated sodium spot in the image plane provides a measure of the average wavefront slope in the subaperture. By integrating the slopes from each subaperture one can construct a map of the wavefront phase error over the entire pupil. In the case of multiple LGSs, the phase information from each LGS is interpolated in order to estimate the phase distortion for light coming from the science target. This increases the field of view (FoV) over which a well-corrected wavefront can be obtained, compared to a single LGS. LGS elongation reduces the accuracy with which one can estimate the centroid of the elongated laser spot and also introduces systematic errors if the mean, intensity-weighted height of the sodium changes. See Fig. 1.2 for reference. Such variability can arise from changes in the density distribution of sodium atoms within the layer. Matched filtering algorithms can provide a higher signal-to-noise measurement of the image position, but the degree of improvement depends on the degree of fine structure present within the sodium layer and its temporal variability.

A second problem arises because changes in the centroid altitude of the sodium cause the images on the WFS to defocus slightly. The AO system cannot distinguish between defocus caused by the atmosphere and defocus caused by variations in the sodium mean
height, making it impossible to keep the science target in focus. For this reason (and another: LGS cannot sense atmospheric “tip-tilt” fluctuations that change the position of the science target) it is essential that natural guide stars (NGS) also be employed. The available stars are generally very faint - sufficient only to provide the lowest order phase information (tip-tilt and focus). Because of this, the focus signal is noisy and has insufficient time resolution to allow the AO system to distinguish perfectly between focus errors caused by the atmosphere and those caused by variations in the sodium profile. Therefore, variations in the sodium centroid, if sufficiently large on small timescales, can cause a significant loss of performance of the AO system.

Initial estimates of the power spectrum of sodium height fluctuations have been made by Davis et al. (2006) who found it to be well represented by a power law, at least at frequencies below 10 mHz. Herriot et al. (2006) estimated that this power spectrum, if it continues to high frequencies, will contribute significant variance to the residual wave front error (WFE) of the TMT Narrow-Field Infrared Adaptive Optics System (NFIRAOS).

With increasing telescope aperture, the complexity of an AO system increases due to the larger numbers of subapertures, actuators on a deformable mirror (DM) and the larger physical dimensions of the optics. With more actuators, higher orders of wavefront distortions can be corrected and hence the mathematical and computational complexity increases, too. However the enormous improvement in telescope performance with AO is the strongest motivation.

Due to the random characteristics of the atmosphere and fast time scales of variation, the update rate that such a system has must at least match the time scales on which the atmosphere changes, which is of order of milliseconds on the smallest scales (highest orders in a WFE expansion function). This demands bright guide stars to provide sufficient photons to permit determination of the wavelength slope on short time scales. If only natural guide stars (NGS) are used, this limits the sky coverage and the usage
of AO on a daily basis for a broad application range. LGS overcome this problem as they provide sufficiently bright backscattered photons from the sodium layer and can be projected at any location in the sky (Herriot et al., 2010).

However, the lowest orders of aberration cannot be corrected by LGS AO systems. With the laser light going up and down through the same atmosphere (round-trip time is $\sim 0.6$ ms, during which the atmosphere does not significantly change), the tip/tilt as well as the focus component of a WFE, imposed on the ray during its path up to the layer is exactly matched on its way down. No net effect is measurable on the WFS. For those modes, which also produce the most contribution to WFE (Noll, 1976), NGSs are needed. These lowest orders change more slowly over the entire aperture and hence longer integration times on a NGS wave front sensor (WFS) can be used to sense such effects. Usual update rates for NGS WFS are in the range of 3 to 10 seconds. Fig. 4.1 illustrates the problem and shows the frequency range above which LGS and NGS information is used for AO correction. Below the limit, indicated by the red vertical line, on longer time scales, NGS information outperforms LGS because the sodium centroid fluctuates randomly, causing large centroid errors, while focus information from long NGS integration is available to keep the science target in focus. Fig. 4.1 also shows the motivation for the UBC lidar project. Before starting the UBC lidar project, no sodium layer data with time resolution shorter than 2 min were available. Thus a wide range of slopes and normalizations were possible (Davis et al., 2006). The light orange region indicates this. Centroid fluctuations also determine the optimum transfer point between the use of NGS or LGS information. The temporal centroid power spectrum is also relevant to the choice of NGS WFSs, because the signal-to-noise ratio depends on the exposure time, which depend on the wavelength range of WFS CCDs. There are many more bright stars at near infrared (NIR) wavelengths, but fast and low-noise cameras are only now under development for this wavelength range. Hence, UBC lidar data with temporal information up to 25 Hz (Pfrommer & Hickson, 2010) give valuable input and
Figure 4.1: Log-log plot of frequency (in Hz) times power spectrum of signals that measure atmospheric turbulence in the basis set of Zernike Polynomials. $j=4$ for example represent atmospheric focus. The high frequency slope is -14/3, as to the Kolmogorov-related -11/3 of the phase-power spectrum, the convolution with Zernike Polynomials brings in 2 more powers of frequency in the denominator. Thus multiplying by $v$ results in -14/3 slopes. This plot is taken from Roddier et al. (1993). To emphasize the NGS/LGS use in AO systems, the readout noise power spectrum for NGS (in blue) as well as the power spectrum for sodium centroid (in orange) has been sketched into this plot.

assistance in answering these questions about sky coverage, WFS CCD development, and LGS refocus mechanisms.

Before giving details of the design, basic lidar theory is introduced and sodium lidar research from the past 30 years is reviewed. Much of this past work, especially when data from many different locations on Earth are combined, helps to understand and interpret the UBC lidar data.
4.2 Theoretical Background

Remote sensing of the atmosphere is actually older than the development of the first lasers in the 1960s. In the 1930s, stratospheric aerosols and molecular density were investigated by means of side-launched continuous-wave (cw) searchlights and a detector that viewed the backscatter cone from the side. Hulburt (1937) pioneered this approach and subsequently Johnson et al. (1939) and Elterman (1966) improved the technique. The first atmospheric studies using pulsed lasers were carried out in 1963 by Fiocco & Smullin (1963) and Collis et al. (1964). Initially, the first backscatter information yielded density proportionalities with no distinct species information. Later, spectroscopic information was obtained by tuning lasers to resonance wavelengths. This allowed the identification of different species and the changes in composition and density at different heights in the atmosphere. The lidar branch of atmospheric research was born and expanded rapidly thanks to its practical applications. Figure 4.2 shows the UBC lidar and its subsystems.

The MLT region is important not only for astronomical applications but also for geophysical science. It is the coldest region in the atmosphere (T ≲ 190 K). Above it, the thermosphere begins and strong absorption of UV and X-ray radiation, mostly by O$_2$, results in higher kinetic temperatures. Little of this high-energy solar radiation reaches the MLT region. The pressure is $\sim 10^{-5}$ to $10^{-6}$ bar. Gravity waves originating from topological obstacles (mountain ridges) or storms in the troposphere (ranging from the ground to $\sim 10$ km altitude) travel upward, increasing in amplitude with decreasing atmospheric density. They overturn and dissipate energy in the MLT region. The high wind shear in the MLT region contributes to energy transport and mixing. Gravity waves have a strong influence on the meridional temperature distribution and meridional wind field (Gardner & Shelton 1985). Located at the boundary between the atmosphere and space, this layer is affected by high-energy radiation and particles of solar and other extra-terrestrial origin as well as influence from gravity waves, planetary waves and tidal
waves (Plane, 2003). This wide range of physics contributes to the difficulty of explaining the observed dynamics and other phenomena. This is discussed further in Section 4.3.

But first, lidar is introduced in more detail. Fig. 4.3 shows the return signal of a lidar pulse propagating through the atmosphere above 20 km, from the UBC lidar system. Rayleigh backscatter can be seen in the lower atmosphere, and the sodium layer is clearly visible above the background noise, starting...
at an altitude of about 82 km and extending in this case to almost 118 km. While this

![Figure 4.3: Semilog plot of a backscatter signal of a sodium lidar with the detector counting photons from the lower atmosphere up to the sodium layer. In the first 80 km, Rayleigh backscatter signal is present in the signal. Just before the sodium layer, the noise floor is reached and the photon count rate increases, this time caused by resonantly backscattered sodium atoms. The slope of the Rayleigh backscatter is in principle proportional to the air density; however, with the 6-m telescope focused on the sodium layer, Rayleigh-scattered photons from lower regions of the atmosphere are defocused and not all photons from a specific height reach the detector with its aperture stop and bandpass filter that only allows transmission within a 1 arcmin FoV.](image)

plot shows a 1 sec integration and 307-m-long height bins, the actual sodium layer data were recorded with 3.6-m bins and 20-ms time resolution. With such an acquisition setup, the background noise per bin is suppressed by the increased height resolution to a few photons in the range between 75 km and the start of the sodium layer. Usually, above 110 km, no backscatter signal is recorded anymore due to the absence of neutral sodium; sometimes however, the signal is extended to 118 km. Narrow bandpass filters
with 0.3 nm width and 90% transmission ensure that only photons from sodium atoms are counted. The sharp rise at the lower end and more gradual fall-off on the high side of the layer is common.

Lidar studies have used many different scattering properties of various constituents of the atmosphere, dependent on the species under investigation. Both elastic and inelastic scattering can be used. Elastic scattering includes Rayleigh scattering (laser wavelength much longer than the dimensions of the scattering object), Mie scattering (laser wavelength and scattering object, like an aerosol, are of comparable size) and resonance fluorescence. Inelastic scattering includes, molecular fluorescence (transition to electronically excited vibronic levels and reemission after relaxation to the lowest vibrational state) and Raman scattering (transition to virtual energy levels and reemission to other rotational or vibrational states in the ground layer). Many different techniques have been developed to study the atmosphere in more detail. However, within the scope of this thesis, these other interesting lidar techniques are not discussed further.

4.2.1 The Lidar Equation

The backscatter signal from the sodium layer is described by the lidar equation \[ N_{ph}(\lambda, z) = \frac{P_{up}(\lambda_{up}) \Delta t}{hc/\lambda_{up}} \beta(\lambda, \lambda_{up}, z) \frac{A_{tel}}{z^2} \eta(\lambda, \lambda_{up}) T_{up}(\lambda_{up}, z) T_{down}(\lambda, z) + \frac{q_{noise} \Delta z}{2c} \] .

It gives the expected number of photons received and counted, \( N_{ph}(\lambda, z) \), from atoms at a range \( z \) at a given wavelength \( \lambda \). This number depends on the number of transmitted photons from a laser with power \( P_{up}(\lambda_{up}) \), laser wavelength \( \lambda_{up} \) and pulse length \( \Delta t \), the scattering probability \( \beta(\lambda, \lambda_{up}, z) \Delta z \) and the receiver probability \( A_{tel}/z^2 \) with the telescope aperture area \( A_{tel} \). The number of received photons also depend on the system efficiency \( \eta(\lambda, \lambda_{up}) T_{up}(\lambda_{up}, z) T_{down}(\lambda, z) \), which includes both the transmitter and the
receiver subsystems as well as atmospheric transmission for the uplink $T^{\text{up}}(\lambda_{\text{up}}, z)$ and downlink $T^{\text{down}}(\lambda, z)$. The detector noise rate and sky background rate in one height bin is taken to be the sum of detected events per unit time with the laser off $q_{\text{noise}}$. While the receiver probability $A_{\text{tel}}/z^2$ should include a $4\pi$ in the denominator it cancels with the isotropic scattering probability $\sigma_{\text{sca}} = 4\pi \beta$. In addition we assume single scattering, where the scattering particles are far enough from each other and exhibit random motion, so that no coherent phase relation between different scattering particles develops. In other words, the sodium layer is assumed to be optically thin, which is a very good approximation as most of the laser beam (97.5%), passes through the layer without interacting with sodium atoms. If we are interested only in sodium layer backscatter and not sodium density, a geometric propagation factor (the inverse square law) can be set to 1; however if Rayleigh scattering from the lower atmosphere is included, the fraction of the defocused lower-altitude beam size that reaches the detector is limited by optical and mechanical restrictions. The UBC lidar was designed to ensure that all photons from the sodium layer altitude range reach the receiver.

It is worthwhile going into more detail regarding the volume backscatter probability $\beta$. This is the probability that a laser photon at wavelength $\lambda_{\text{up}}$ over a unit distance (the scattering layer thickness $\Delta z$) will scatter a photon at wavelength $\lambda$ into a solid angle at an angle $\vartheta = \pi$ (measured from the direction of the incident beam). Hence the product $\beta \Delta z$ represents the angular backscatter probability and implicitly includes the sodium column density $C_{\text{Na}}(z)$, which is taken for each height bin $\Delta z$. The volume backscatter coefficient for sodium can be written as

$$\beta(\lambda, \lambda_{\text{up}}, z) = \int \left[ \frac{d\sigma(\lambda)}{d\Omega} C_{\text{Na}}(z) f(\lambda) \right] d\lambda ,$$

with $d\sigma(\lambda)/d\Omega$ being the differential scattering cross-section, the probability that a single particle is scattering a photon at wavelength $\lambda$ in the solid angle $d\Omega$. $f(\lambda)$ is the
fraction of laser photons having a wavelength in the range $\lambda$ and $\lambda + d\lambda$. The scattering cross-section can be derived from basic principles and is shown in Section 4.2.2. With the help of Eqn. (4.1), the return flux can be estimated. This is outlined in Section A.5 and as derived there, care has to be taken in case of saturation of the sodium layer. This is the case for the UBC lidar system and hence the absorption cross-section, is used in a different way to estimate the return flux (see Appendix Chapter A.5). In the following section, basic sodium properties with respect to the cross-section are reviewed and a derivation of the absorption cross-section is given.

### 4.2.2 Sodium Properties

This section uses sodium data from Steck (2009) and summarizes the most important sodium properties for lidar applications. Sodium has only one stable isotope with the configuration $^{23}\text{Na}$. Thus, no mass-shift due to isotopes or field effects have to be considered. The atomic mass is 22.989769280(28) u, which translates to $0.381754035(19) \times 10^{-25}$ kg and its nuclear spin is $I = 3/2$. For sodium lidar applications, the sodium D$_2$-line is used, and its transition wavelength in air is 588.997 nm, using Eqns. (2.1) and (2.2) under normal conditions at the location of the observatory (970 mbar pressure and a temperature of 288 K). This wavelength was used during the design process to identify the correct bandpass filters. For the conditions in the sodium layer (1 Pa, 190 K), the transition wavelength is almost that of the vacuum, 589.158 nm. So with the laser tuned at the observatory at 588.997 nm, the correct transition wavelength will be achieved in the sodium layer. With the Doppler-broadened absorption line confined within $\sim$3 GHz ($\Delta\nu_{FWHM} = \sqrt{8kT \ln 2/(mc^2)}\nu_0$ for each of the six hyperfine transitions), which translates to $\sim$5 pm at 589 nm, precise tuning of the laser pulse is essential to maximize the return signal. The excitation lifetime is 16.249 ns, long enough that a single atom is excited no more than once during the 6 ns long laser pulse. The D$_2$-line results from the
3^2S_{1/2} \rightarrow 3^2P_{3/2} \text{-transition.}

To investigate the optical transition, the electronic transition is now described in detail. Usually for the fine structure, the sum of the total angular momentums of the body electrons, containing angular momentum as well as spin, must be added to the angular momentum of the optical electron (the electron making the transition). However, with sodium, only one valence electron is present, while all other electrons reside in closed shells. Thus only the optical electron’s angular momentum \( \vec{L} \) and its spin \( \vec{S} \) are summed to form the total electron angular momentum \( \vec{J} = \vec{L} + \vec{S} \) with quantum numbers \( J \) satisfying \( |L - S| \leq J \leq L + S \). Thus the D-line is a transition of the valence electron’s angular momentum from excited \( L = 1 \) (P-state) to \( L = 0 \) (S-state), while the D\(_2\)-line specifically describes the transitions from the \( J = 3/2 \)-level in the excited state.

This fine-structure splitting, described by the quantum number \( J \), is further split into sub-levels as the total electron angular momentum \( \vec{J} \) interacts (couples) with the nuclear spin \( \vec{I} \) (which is non-zero for sodium) to form the total atomic angular momentum \( \vec{F} = \vec{J} + \vec{I} \). Again the length of the total atomic angular momentum \( \vec{F} \) can take values from \( |J - I| \leq F \leq J + I \). Thus the ground state \( (J = 1/2, I = 3/2) \) employs two hyperfine levels \( (F = 1 \text{ and } F = 2) \), while the excited level for the D\(_2\)-line \( (J = 3/2, I = 3/2) \) employs 4 hyperfine levels \( (F = 0 \text{ to } 3) \). Thus, energy shifts due to the hyperfine interaction must be taken into account in order to calculate the correct absorption coefficient spectrum. This consideration is detailed enough for the short pulse of a lidar system. In case of a continuous-wave laser system, important to LGS AO systems, the magnetic field of the Earth and its coupling with the sodium layer must also be considered. Holzlöhner et al. (2010) calculate this effect for different mid-latitude sites. Dependent on the laser position on the sky, the magnetic field influence might decrease the photon return flux by as much as a factor of 3. For every quantum number \( F \), \( 2F + 1 \) sublevels exist, with slightly different energy levels and selection rules (Moussaoui et al., 2009).
4.2.3 Hyperfine Interaction

The energy levels are shown in Fig. 4.4 for the $^{3}_{2}\text{S}_{1/2} \rightarrow ^{3}_{2}\text{P}_{3/2}$-transition (D$_2$-line). The theoretical background of the hyperfine interaction is described in Appendix B. Recognizing selection rules, a total of six single hyperfine lines must be considered. They are summarized in Table 4.1. Energy shifts for the single terms, where the dipole and quadrupole contributions are added together and the difference between the two different $F$ quantum numbers is taken, are calculated. The necessary hyperfine-constants are listed in Table B.1 of Appendix B.

$$E_{\text{HFS}} = E_{\text{Dip}}(I,J,F) + E_{\text{Quad}}(I,J,F) = \frac{C}{2} \cdot A + \frac{B}{4} \cdot \frac{3C(C+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)} \quad (4.3)$$

In Appendix B the line strength and the chosen line profile, necessary for the final absorption cross-section calculation, are explained. Fig. 4.5 shows the final result of the absorption cross-section spectrum $d\sigma/d\Omega$ in m$^2$ per unit solid angle and unit frequency.
Figure 4.4: Energy level diagram for the D_{2}-transition with fine- and hyperfine splitting. In addition to the respective energy differences, Landé g_F-factors are given with the corresponding Zeeman-splitting energy differences for magnetic sublevels, from Steck (2009).
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in blue, where the relative intensities have been multiplied by the oscillator strength 
\( f = 0.640139 \) (Steck, 2009), and a factor (outlined in Appendix A.3),

\[
\frac{1}{16\pi\varepsilon_0} \frac{q^2}{m_e c} \quad .
\]  

\( (4.4) \)

**Figure 4.5:** Simulated absorption coefficient spectrum of the sodium D\( _2 \)-line (\( 3^2S_{1/2} \rightarrow 3^2P_{3/2} \)-transition). The six single hyperfine lines are also plotted to show the contributions of each line. In addition the envelope of the laser line has been added for clarity.

The center of the line is given in air, but shifted for mesospheric conditions (\( T = 190 \) K, \( p = 1 \) Pa).

### 4.3 Sodium Layer Research in the Upper Mesosphere and Lower Thermosphere

The sodium layer has been subject to many studies over the past 30 years, covering a wide variety of latitudes as well as longitudes on Earth. In 1929, a sodium nightglow
was first recognized and studies began using sunlight as the excitation source during twilight as well as searchlights with photographic detector techniques. Direct sodium density measurements started with the development of tunable laser sources (Bowman et al., 1969).

4.3.1 General Sodium Layer Statistics

In the late 1970s, Megie & Blamont (1977) studied global properties of the sodium layer with 3 years of data obtained with a lidar system at the Haute Provence Observatory in the French Alps using a 0.8 m telescope. They studied the sodium abundance variability on a seasonal and monthly time scale, top and bottom variations in the sodium layer and tried simulating the source of the sodium with a photochemical and dynamical model. They found that regular photochemical processes at nighttime together with the absence of systematic seasonal and diurnal changes explain the data and concluded that a permanent source of sodium of variable intensity at the top of the layer might account for the random variability. This was the first evidence that meteor influx is the source of sodium. They also report sporadic enhancements of local sodium density and regarded this as more evidence for meteoric origin of the mesospheric sodium. With sodium serving as a tracer of mesospheric dynamics, the observed stratification within the sodium layer implicated organized motion in the mesopause, which points to gravity waves. In 3 years of data, they found a general enhancement of sodium column density in November and December (up to $8 \cdot 10^{13}\text{m}^{-2}$) (Megie et al., 1978), and a slight enhancement in February with an otherwise stable column densities of $\sim 2-3 \cdot 10^{13}\text{m}^{-2}$. They concluded that a large vertical transport of terrestrial particles into the sodium layer region occurs in northern winter to account for the difference. Clemesha et al. (1979) shows however that, at least for southern mid-latitudes at 23°S (San Jose dos Campos in Brazil), strong seasonal as well as winter sodium abundance variability were observed. For northern lidar stations at
latitudes from 23°N to 32°N, this has not been observed, apart from a strong November maximum. Rather than terrestrial origins, it appears, according to Clemesha et al. (1979) that seasonal changes in mesospheric temperature causes the equilibrium between sodium and its oxides to shift, and hence oxidation reactions are responsible for column density changes.

Even though this conclusion was drawn from only 5 years of sodium data collection, this explanation was later recognized as the correct assumption and it has been refined successively in the following decades. Plane (2003) summarizes the status and concludes that meteors are the most significant source for the sodium layer, based on good correlation from relative abundances of metallic ions in the MLT and their elemental abundances in chondritic meteorites as well as enhancements of metals in the MLT during meteor showers. Sodium abundance is 0.6% in meteors. Plane (2003) and Love & Brownlee (1993) suggest a significant fraction of the microgram meteoroids to be of asteroidal origin but some meteors in the microgram range might also have cometary origin. von Zahn et al. (1999) conducted lidar measurements using several different lasers, tuned to resonance transitions of iron, potassium, calcium and sodium to study the ablation process in detail and found strong evidence for differential ablation. The general accepted column density is now around $4.5 \times 10^{13} \text{ m}^{-2}$ with variabilities that can range up to a factor of 10, dependent on time and location. While the November enhancement is very small at low northern latitudes and shifted towards an August maximum at southern low latitudes, at mid-northern latitudes this enhancement can reach a factor of 3, and in polar regions a factor of 10 has been observed. Plane (2003). This correlates well with temperature variations in this region and points to a high sensitivity of mesospheric metals to temperature variability. The sodium layer’s full width at half maximum is $\sim 10$ to 12 km. High resolution temperature structure measurements in the sodium layer have been pursued by Fricke & von Zahn (1985) and She et al. (1992), by probing the Sodium D$_2$-line at different spectral locations with a narrow band laser.
An impressive temperature resolution of 3°C near the sodium layer peak was obtained. These efforts resulted in a model that explains the annual variations in the temperature structure, by combining data sets from Fort Collins, United States (41°N) and Kuehlungborn, Germany 54°N (She & von Zahn 1998, von Zahn & Höffner 1996). Together with data from 70°S to 70°N (Luebken & von Zahn 1991, Bills et al. 1991), a global picture was derived. In the following, seasons are defined for the northern hemisphere unless specifically mentioned “southern”. Fig. 4.6 depicts the two-level mesopause concept and is taken from She & von Zahn (1998) for clarification. In winter the mesopause resides at about 100 km, whereas in summer it is around 88 km height. While in winter, a latitude-independent mesopause exists (i.e. all latitudes experience the coldest temperatures around 100 km), in summer no distinct mesopause region at 88 km can be determined for low latitudes, which means the temperature is not significantly smaller at one specific altitude but around 190 K to 200 K throughout the MLT region. From mid to high latitudes in summer, the temperature decreases rapidly from 180 K to 130 K, and stays at a constant height of 88 km. During the transi-
tion in fall and spring, the mesopause region changes its shape relatively sharply. The 100 km region shows annual variations in the minimum temperature of 3-4 K. However, the region around 88 km shows strong annual variations with cold summers and warm winters. This is latitude-dependent and the temperature variation can reach up to 50 K in polar regions. No such two-level (in altitude) change is found in the sodium density. Over an 8-year data set, the November maximum in column density is \(6 \times 10^{13} \text{m}^{-2}\). This is mostly confined to the inner regions of the sodium layer, and a less prominent peak is seen in February. A minimum density of \(1.7 \times 10^{13} \text{m}^{-2}\) was seen at Fort Collins in June (She et al., 2000). Similar results were also found with data from the ODIN satellite in the latitude band 35\(^\circ\)N to 40\(^\circ\)N (Gumbel et al., 2007). Limb day glow was observed with 2 km height resolution of the upper atmosphere between 40 km and 110 km over 5 years using the on-board OSIRIS spectrometer with a spectral resolution of 1 nm at the sodium resonance line. Radiative transfer is used to determine the sodium column density and calibrate against ground-based lidar from Fort Collins (She et al., 2000) and Urbana (States & Gardner, 1999). The November peak as well as the minimum in column abundance in summer is clearly seen. In addition, the column density increases with increasing latitude. Specifically the peak density increases, which points to the fact that temperature has an influence on the column density, and a warmer lower limit in the sodium layer results in increased sodium abundance. For GOMOS data, a spectrometer onboard the ENVISAT satellite that measures limb radiation via stellar occultation, Fussen et al. (2010) derived a global model for sodium column abundance. Their result, from 6 years of data, is shown in Fig. 4.7. It shows a band of minimum sodium abundance, extending from the South Pole in January, to the North Pole in June/July, which becomes less prominent the equatorial region. The highest sodium abundances are seen near the pole for the northern hemisphere, and at around 65\(^\circ\)S for the southern hemisphere. In the low and mid-latitude regions, the semiannual variation is seen. A study of peak concentrations shows strong enhancement for November in
Figure 4.7: Sodium column abundance from the GOMOS satellite. Raw data is seen in the upper panel, and the lower panel shows a model that fits the data and gives a general global sodium abundance picture, from Fussen et al. (2010).

The northern hemisphere, while the enhancement is less prominent and shifted from November towards August for low latitudes in the south. This connects different findings from different ground-based lidars all over the world into a global picture. Closer to the South Pole, a semi-annual behavior becomes prominent, giving rise to a second maximum in sodium abundance in February. While such satellite data reveal the global picture, local sodium variability is still very high and easily overrides the global mean. This may be due to overturning (unstable) gravity waves and subsequent eddy diffusion as well as tidal waves that input energy into the sodium layer from below. Local sporadic meteor influx can also cause changes in the ionosphere’s electron abundance as can high-energy
solar radiation. All these environmental influences are short-lived, but are able to change sodium structure and dynamics significantly and give rise to the observed variability over one night. But there should be little effect on a monthly trend analysis, other than large error bars from year to year (Plane, 2003).

The centroid altitude varies semiannually with two maxima in early spring and late fall at around 92 km, a global minimum in summer around 90.5 km and a less distinct minimum near the end of the year at \( \sim91.2 \) km (Plane et al., 1999; She et al., 2000). The rms sodium layer width, also shows semiannual variations, however this time with minima in fall and spring and a global maximum in winter, while the summer maximum is less exposed (Plane et al., 1999). Hence sodium layer width and centroid height are varying annually out of phase for northern latitudes. For the southern low latitudes, Clemesha et al. (2004) reports a long-term analysis with over 30 years of sodium layer data at 23°S. These data also show a semiannual variation of centroid height, with maxima around 92.3 km in spring and fall, though less distinct. However, the variations are in phase with the northern counterparts. Yet, the global minimum in winter, with a centroid height around 90.5 km, is also clearly present. Moussaoui et al. (2010) performed an interesting study with the 35 year data set of Clemesha. With the aim of extracting AO-relevant parameters such as sodium centroid height, thickness and sodium abundance, the authors also studied daily variability over the year. From their analysis, the semiannual variability in thickness and centroid height is present, but the daily variations are significantly higher and do not show a clear trend over the year, indicating the local short term influence of energy and momentum input through wave interaction and wind shear. From the monthly mean in centroid height, the maxima in early fall/late summer and spring can be seen, however the variations from year to year are large and hence only a strong minimum in November is significant. Recently reported are seasonal variations in the sodium layer from Gadanki, India (14°N) (Vishnu Prasanth et al., 2009). Their data might be affected by strong gravity-wave influence, originating from the Himalayan
mountains, but nevertheless, this is a very interesting data set to understand the global variability of sodium in the MLT region. Such local effects might explain the generally higher level of sodium abundance, by at least a factor of three, compared to all other ground-based lidar stations. Their dataset spans two years. A maximum in column density was observed in September/October, whereas a less pronounced maximum arose in spring. Unless for other lidar sites the annual column abundance variability shows less seasonal amplitude than for other northern sites, including a study from Hawaii at almost the same northern latitude (Roberts et al., 2007). Their sodium layer width also shows semi annual variations with maxima in fall and spring. Interestingly, the annual monthly mean of the sodium centroid does not seem to be out of phase and also shows a minimum in spring, while for November, more data is needed. In total, it seems that low-latitude sites show less variations in sodium layer parameters, compared to mid and high latitudes, also reported by States & Gardner (1999). The study in India (Vishnu Prasanth et al., 2009) can be directly compared to a 3 year data set from Haleakala on Maui, Hawaii, at about the same northern latitude (19°N), conducted by Roberts et al. (2007). Their results of sodium column abundance are comparable to mid-latitude general findings, indicating a slight increase in November, and a minimum in summer, while the rest of the year exhibits strong daily variations with a rather constant mean level around $4 \cdot 10^{13} \text{m}^{-2}$. While Roberts et al. (2007) point to the large daily column density variability and therefore large deviation from a monthly mean, it seems to be completely in line with the global picture, drawn by the model, derived from satellite data, shown in Fig. 4.7 by Fussen et al. (2010) that conclude less variability for low latitudes, especially a distinct change in the latitude range between 40°N and 20°N.

All these findings point to following summary regarding basic sodium layer parameters. The most important source for metallic sodium are meteors. Ceplecha et al. (1998) reports the meteor influx function for the Earth and finds that it peaks around $10^{-5}$ g with about $10^6$ or $10^7$ kg/year/earth in one decadal range of mass. This is shown in
The meteoric dust that rains on Earth every day is the main contributor and dominant micrometeor species. Figure 4.8: Differential meteor influx function, indicating in which decade of mass range the most mass falls on Earth per year. Micrometeors, like dust particles, with masses $\sim 10^{-8}$ kg to $10^{-9}$ kg rain on Earth and dominate the mass flux on an average yearly basis. The microgram particles completely ablate in the highest regions of the atmosphere between 120 km and 75 km. The second peak on the high mass range results from very rare huge impactors, and hence are of little importance to the daily mass balance (von Zahn, 2005). The second curve, marked with B results from a satellite experiment (long duration exposure facility, LDEF), where Love & Brownlee (1993) studied sub-millimeter-sized impact craters on a satellite surface, exposed almost six years in space. A later correction to faster impactor velocities (von Zahn, 2005) brought the curve down to the influx, indicated by the continuous line. This line represents measurements from radar echoes of meteor influx, ground-based visual and camera measurements and satellite impacts and ionisation measurements, from Ceplecha et al. (1998).

Ablates completely in the upper region of the atmosphere. With densities of about 2 g/cm$^3$, the typical mass of a dust grain is less than 100 µg, frictional heating vaporizes the material (Plane, 2003).
After being deposited in the MLT region, or in the ionosphere, above as ions and then recombined with free electrons on its way to lower altitudes, sodium undergoes a complex chemical reaction chain. While August is the peak of meteoric infall, the cold bottom part in the sodium layer seems to remove material easier, which results in small sodium abundances in northern summer. This is on first sight counterintuitive as reaction rates usually increase with temperature, however the chemistry of removal is not a simple reaction and involves many steps. According to Plane et al. (1999), the main reactions involve sodium reacting with ozone to form NaO which, with hydrogen from water molecules, reacts to NaOH. This reacts with CO\textsubscript{2} and a metal as catalyst to NaHCO\textsubscript{3}. So to remove sodium ozone is important, and in warmer winters, not as many oxygen radicals are available to form ozone and hence this reaction is suppressed.

Atomic oxygen is mainly produced during the day and subsequently merged with molecular oxygen at night (Plane et al., 1999). Above 82 km, the low-pressure limit of sustained atomic oxygen is reached, and hence this species exhibits a large diurnal variation, also known as the atomic oxygen shelf (Plane, 2003). This is caused by direct sunlight imposing photo ionization and charge exchange, followed by recombination mechanisms throughout the night (States & Gardner, 1999). At the beginning of the night, lidar measurements usually indicate a wider sodium layer, which thins over the first 2 hours of observation; see Fig. 9.1, or Pfrommer et al. (2009). Thus the Sun-influenced production of oxygen radicals are still present at the beginning of a night and hence more sodium can be removed from the lower parts in the sodium layer where sufficient H\textsubscript{2}O and CO\textsubscript{2} are present. This removal causes the rise of the lower limit of the sodium layer during the first few hours after sunset. While in lower sodium layer regions, the observed density is correlated with temperature; this is not the case in higher regions and hence ion recombination, which is not temperature driven, as well as meteoric influx play a major role above 96 km (States & Gardner, 1999). As shown by Moussaoui et al. (2010), this causes daily fluctuations of the vertical sodium structure and hence column
density, thickness, and centroid height.

### 4.3.2 Summary

To summarize the main sodium layer parameters, following Table 4.2 shows the main trends and typical values for different latitudes and months. The mesopause temperature variations have already been summarized in Fig. 4.6.

**Table 4.2:** Summary of typical sodium layer parameters.

<table>
<thead>
<tr>
<th>Sodium layer parameter</th>
<th>Trend</th>
<th>Maximum</th>
<th>Typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Col. abund. [m(^{-2})] high N lat.</td>
<td>annually</td>
<td>8·10(^{13}) (Nov.)</td>
<td>2·10(^{13})</td>
</tr>
<tr>
<td>Col. abund. [m(^{-2})] mid N lat.</td>
<td>annually</td>
<td>6·10(^{13}) (Nov.)</td>
<td>3·10(^{13})</td>
</tr>
<tr>
<td>Col. abund. [m(^{-2})] low N lat.</td>
<td>annually</td>
<td>5·10(^{13}) (Nov.)</td>
<td>4·10(^{13})</td>
</tr>
<tr>
<td>Col. abund. [m(^{-2})] low S lat.</td>
<td>annually</td>
<td>8·10(^{13}) (Aug.)</td>
<td>6·10(^{13})</td>
</tr>
<tr>
<td>RMS width [km]</td>
<td>semiann.</td>
<td>~5 summer/wint.</td>
<td>~4.1 spring/fall</td>
</tr>
<tr>
<td>Centr. height [km]</td>
<td>semiann.</td>
<td>~92 spring/fall</td>
<td>~90.5 summer/wint.</td>
</tr>
</tbody>
</table>

⇒ Less annual variation in sodium layer parameters for low latitudes.

**Daily variations**

| Daily change in col. abund. | ~50% standard deviation from monthly mean |
| Daily change in centr. height | ~1 km standard deviation from monthly mean |
| Daily change in width       | ~0.5 km standard deviation from monthly mean |

⇒ Strong daily variations in all sodium layer parameters for all latitudes.

### 4.3.3 Sodium Layer Dynamics

With sodium being a tracer of mesospheric dynamics, Shelton et al. (1980) report correlation of observed sodium profiles from the Urbana, Illinois lidar system with
gravity wave simulations that model the sodium layer response. They find that a simple linear response is not enough and non-linear expansions on the gravity wave models are necessary. This is justified by the low density in the mesopause and the expected non-linear growth and subsequent dissipation (Gardner & Shelton, 1985).

Observations of dynamics in the sodium layer can help in the understanding of the general sodium evolution process. Turbulent mixing through wind shear, local temperature changes, and gravity-wave energy deposition all contribute. Sodium-layer dynamics have therefore been investigated since the early 1980s. She et al. (1991) first derived the buoyancy frequency from high-resolution temperature measurements and also determined Richardson numbers (Ri). These help to understand the local gravity wave interaction with the sodium layer. The Buoyancy frequency is the maximum frequency a gravity wave can exhibit, with buoyancy being the restoring force. The Ri-number is the dimensionless ratio between potential and kinetic energy. If Ri > 0.25, turbulent mixing occurs, causing small-scale fluctuations in the sodium layer and structural changes on short time and spatial scales. Collins et al. (1996) also used direct measurements of the buoyancy frequency to derive velocity perturbations. Comparing the diffusivity of the gravity wave field from their measurements with results from low, mid and high latitudes, they conclude that it does not vary significantly with latitude and could be modeled using diffusive-filtering theory (DFT). This means that waves, whose vertical velocity of the momentum diffusion exceed the vertical phase velocity, are severely damped and therefore not present in the spectrum (Gardner, 1998). Note that this conclusion is confined to the applicability of DFT and the general interaction of gravity waves with the sodium layer. There are certainly regions on Earth with more upwelling gravity waves compared to others, and hence the sodium layer in those regions is more affected than others.

Theoretical models have been refined in subsequent years (Gardner, 1998) to take into account gravity-wave interactions in other parts of the atmosphere (Russell & Sica, 2001). The temporal gravity wave power spectra are well represented by power laws, with indexes
ranging from -1.5 to -2.0 below frequencies corresponding to 16 min periods. Above this frequency however, much more variability has been observed, which points to energy dissipation influences. Fritts & Alexander (2003) describe gravity wave interaction with wind, and the influence on stability as well as the evolution with height in a thorough review. They derive constraints on the wave structure and stress the applications to large-scale climatology and circulation. While gravity waves explain variations in the sodium layer structure on time scales of minutes or hours, diurnal variations have been attributed to photochemical effects, removing more or less sodium depending on the amount of atomic oxygen, which is directly related to the solar cycle (States & Gardner, 1999). However, as stated by Clemesha et al. (2002), at the height of the sodium layer solar-atmospheric tides have an influence on the sodium structure. By simultaneous measurements of horizontal wind from meteor radar measurements, they find a close correlation of sodium density oscillations with tidal wind having 12 hour and 24 hour cycles. While this does not rule out photochemical influences, it does point to a combined effect of both phenomena.

One paper has been found that describes short-term variability in the sodium layer, which is the topic of parts of this thesis. O’Sullivan et al. (2000) use the Calar Alto (37°N) LGS cw laser system and observe the resulting elongated sodium obliquely, using a 2d photon counting device on the 3.5-m telescope, located 300 m away from the laser launch site. Rebinning of data into 100-ms bins shows a centroid height variation that exhibits strong short-term changes, sometimes 400 m within 1 to 2 min. No power spectra were published. This short data set of 3 nights showed the first evidence of strong short-term variability on ~1 sec time scales. Davis et al. (2006) subsequently analyzed 2-min-integrated data from the CSU lidar (She et al., 2000), and found the sodium layer centroid power spectra with power indexes ranging between -1.9 to -2.1. However, for an LGS relevant time scale, this data set did not provide faster sampling rates. This motivated the UBC lidar experiment, described in this thesis.
4.3.4 Sporadic Sodium Layer

While gravity waves may explain the evolution of the stratified profile, they appear to be unable to account for sudden strong enhancements, lasting from minutes to several hours. Clemesha et al. (1980) reports such a sodium cloud, whose origin was, according to their observations, a 10-kg meteor. However they reported a horizontal extend of order 100 km, while the vertical extend is only 1 km. With many researchers reporting sporadic layer observations over the years (Kwon et al., 1988; Gardner et al., 1988; von Zahn & Hansen, 1988), Clemesha et al. (1988) proposed a formation mechanism, involving meteoric origin, large clouds and subsequent horizontal thinning by strong wind shear. In recent years this explanation has been refined and ion recombination above the sodium layer seems to play an additional role (Clemesha et al., 1999; Collins et al., 2002; Williams et al., 2007).

This is a less important aspect in terms of influence on AO, because the sporadic layers are reported to form on time scales of minutes or at least 10 to 20 seconds, and the AO system should be able to adapt to follow such changes. However, there is reported variability within the sporadic layers (Liu & Yi, 2009) that might cause problems for AO systems because variability in a strongly enhanced, localized cloud could cause the centroid height to change rapidly. In the UBC lidar data, sporadic layers have been seen and a study is planned in the near future to investigate the variability. The high photon return of the UBC lidar system should enable us to investigate the phenomenon on time scales of about one second.
Part II

Design/Operation and Results from Lunar Scintillometers
Chapter 5

Design and Operations of Lunar Scintillometers at Northern and Southern Mid-Latitudes and in the Canadian Arctic

5.1 Design Aspects and Operation of the CTP at CTIO

The Chilean Turbulence Profiler (CTP) had already been designed when I joined the project and hence I will summarize the important parts and not go into detail, as it is not a design to which I actively contributed.

The CTP employs a linear array of \( n_D = 12 \) diodes, separated such that each diode gives a unique baseline. The number of baselines is \( [n_D \cdot (n_D - 1)]/2 \); in this case, 66. The acquisition electronics, designed by the UBC department of physics and astronomy electronics shop, records integrated intensity from the Moon at a 100-Hz rate. Hence, 12 AC intensity recordings are stored every 10 ms on disc. It is important that each diode is read out at the exact same time as the atmospheric turbulence changes on time scales of a few milliseconds.

To ensure a meaningful covariance value for each diode pair, 6000 values are taken over 1 minute, from which the covariance is computed. The details of the theoretical
derivation are given in Section 3.3.

To decrease the sky background radiation, \(\sim 15\) cm long tubes of diameter 20 mm are placed in front of each diode, so that the field of view for each diode is reduced to a radius of \(\sim 4^\circ\). With such a field, the scintillometer needs to track the Moon. For this reason, it is mounted on a Losmandy German equatorial mount and controlled with the Gemini Astronomical Positioning System. This system can be connected to a computer and serial commands are used to interact with it.

Initially we added a 15-cm telescope, on which a 2\(k\) x 2\(k\) CCD camera is attached. In a later update this telescope was replaced with a 25-cm Meade telescope. The primary goal of this camera system is to take pictures of the Moon every 20 sec. This project is called “moonpatrol” and we are working in collaboration with A. Crotts from Columbia University, New York, in order to detect and statistically analyze transient lunar phenomena (TLP). Amateur astronomers as well as Apollo astronauts have reported these events, however a long-term statistical data set is lacking. As we are already tracking the Moon and need an imaging system for guiding, this small add-on allows us to do additional science. Due to the already large extent of this thesis, it was decided to not go into more detail on this project. However the interested reader is referred to Crotts (2008), Crotts et al. (2008, 2009), Crotts & Hummels (2009).

To simplify remote observing, a webcam with a Nikon camera lens was added to help find the Moon if the mount loses its calibration. A control program, written in Labview, mostly by P. Hickson, is used to control each component of this setup. It communicates with the mount, incorporates the autoguider and controls CTP and CCD camera data acquisition.

We have been observing with this instrument since June 2007, whenever the Moon phase is larger than 40\%, the Sun is lower than -12\(^\circ\) in altitude and the Moon is higher than 30\(^\circ\) in altitude on the sky. If these criteria are fulfilled and if the weather is suitable for observing, the staff at CTIO opens the roof of the enclosure. A roof switch ensures
Figure 5.1: The location of the CTP on the CTIO summit at sunset is indicated with the circle. In the upper left part, the 4 m Blanco telescope dome is visible. The 12-element array is clearly visible in the lower left and right cut-out. The shed is manually opened by the CTIO technicians every evening, weather permitting, and the CTP wakes up autonomously if the observing conditions, set by the Moon and Sun position are fulfilled. Tracking is provided via in-house autoguider that reads out the CCD images from the 2k x 2k CCD camera, which is mounted on a 25 cm Meade Schmidt-Cassegrain telescope. The small webcam, visible in the lower left panel just right of the Meade telescope, is used for remote controllability.

that the autonomous program is aware of the state of the roof and only starts if the roof is open.

Over the course of time, refinement of the control program reduced the interaction necessary with the system during observations. However, to ensure the best data, a check every night was made via remote connection to Vancouver.

More details on the observing procedure can be found in Gagné (2010). R. Gagné
Figure 5.2: A screenshot of the main control programs, during observing. The upper left part shows the serial interaction mask, when direct communication to the mount is necessary, in case the autonomous program, seen on the right side, fails to correctly communicate. This happens if the mount loses its coordinates and the position of the Moon has to be found by hand. After synchronizing, the control program takes over again. In the control program, the upper right side shows the real time data from the CTP via 12 bar graphs. The other parameters on this panel are lunar position, mount parameters and CCD control parameters. In the lower left corner, two webcam images help the remote controllability. The little image shows the Moon through the camera lens and the larger one shows the array position as the green LEDs on the right side in the image indicate the position at night. Especially during the day this webcam is used to ensure the correct mount communication.

took over observing from me in October 2009 as part of his thesis. Data acquisition, remote operations, trouble shooting and repairs were tasks that P. Hickson and I shared over the period of operation of the CTP. A reduced data set was published by Hickson et al. (2009).
5.2 Design and Operations of the ATP at PEARL on Ellesmere Island, Nunavut

The site test campaign in the Canadian Arctic is introduced and summarized in Chapter 6, Section 6.1 as is the framework into which the lunar scintillometer for the Arctic (the ATP) fits. A more detailed discussion of astronomy-related meteorology in the Arctic was published by Steinbring et al. (2010). Even though I am a co-author on this paper, it is not part of this thesis as I was only part of the field team in 2009, whereas the main part of this paper covers the years 2006 to 2008.

5.2.1 ATP Deployment – Topology and Meteorology

The ATP was deployed in the Arctic at the Polar Environment Atmospheric Research Laboratory (PEARL), run by the Canadian Network for the Detection of Atmospheric Change (CANDAC) under the direction of J. Drummond of Dalhousie University. They kindly agreed to host our instrument and if necessary, provide technical support. PEARL primarily hosts instruments to detect atmospheric climate change. A total of about 25 instruments are taken care of by one technician, so instruments must be mostly independently operational and reliably working in order not to impose more work than necessary on the one-man PEARL staff during the winter months. The site, shown in Fig. 5.3, is located ~15 km from the Eureka Environment Canada (EC) weather station on a ridge at 615 m above sea level. It is bordered by Eureka Sound to the west, Greely Fjord to the north, and Slidre Fjord to the south. To the west and south, the local topography falls steeply. Towards the east and north, a gently-sloped topography is found. Further to the west, on Axel Heiberg Island, glacier-covered mountains as high as 2200 m are found. Directly 400 m to the west of the PEARL site, an equally high parallel ridge is located. This might affect the local turbulence, during westerly winds. Because of this surrounding topography, we believe that PEARL is not the best
Figure 5.3: The left panel shows the northern tip of Ellesmere Island, with the 4 remote mountain peaks, identified as potential telescope sites as discussed in Section 6.1. The current site test location for the ATP is at PEARL, south of the Greely Fjord and east of the Eureka Sound. The right panel shows the detailed location of Pearl and the 15 km distant Eureka, because the red cross, indicating the PEARL location on the left panel is misleading. North is also facing up on the right panel, from Hickson et al. (2010).

possible site on Ellesmere Island. PEARL was chosen to take advantage of direct internet communication, year-round manpower, local access to an air strip and power. Its flat roof provides an ideal location. Cables are routed to a warm room inside, where data cables, communication cables and power cords are connected. Fig. 5.4 shows the PEARL lab as seen from the south. Over the last 50 years, climate data have been measured at Eureka (Bourdages et al., 2009, Lesins et al., 2010). The monthly average temperature over the winter months fall continuously from $-31^\circ C \pm 3^\circ C$ in November to $-38^\circ C \pm 3^\circ C$ in February. With the first reappearance of the Sun, the temperature rises in April to $-28^\circ C \pm 2^\circ C$. A winter boundary layer develops during November and December and is stable over the coldest months, January to March. Radiative cooling of the surface causes this inversion layer. The average wind speed in winter is $2.5 \text{ ms}^{-1} \pm 0.5 \text{ms}^{-1}$. This wind speed, measured in Eureka at sea level, is surprisingly low. According to Lesins et al.
The strong and stable temperature inversion caused by the cold surface, does not allow for momentum transfer to the surface with higher elevations and as a result, such low wind speeds are measured near ground level. The calm conditions are also favorable to the inversion condition and this stabilizes the meteorology. Wind direction is affected by local topography and with the Slidre Fjord extending to the west and southeast, those directions are typically measured throughout the year. However, in winter calm conditions were registered 39% of the time compared to the summer months where calm conditions are recorded less than 5% of the time. The average cloud cover is reported to be 30%±10% and the precipitable water is measured to be 2 mm±0.5 mm over the winter months. The winter inversion layer in the Eureka region has been stable over the past two decades at the EC site and extends up to ∼1100 m. The top of this layer is
defined by the maximum temperature in the atmosphere.

Apart from the cold environment and the associated challenges for instruments, machines and humans, the meteorology is very favorable for astronomical observations. The same conclusion was drawn in Steinbring et al. (2010), where even more favorable sites on the northern end of Ellesmere Island at 82.5°N were assessed with basic weather stations. In addition these mountain sites are, with their height of at least 1100 m, above the inversion layer and hence very low optical turbulence during the winter months is expected. This has yet to be proven and for this reason we plan to redeploy the ATP following testing at PEARL on one of the remote mountain tops, indicated in the left panel of Fig. 5.3.

5.2.2 General Design Aspects of the ATP

A set of 8 diodes is placed around a circle in a ring module, as outlined in more detail later in this chapter. Compared to the previous CTP design with a horizontal diode array, the ATP employs six ring modules, stacked together on a vertically extended post, making it a six-element array (see Figs. 3.3 and 3.4). One diode from each ring faces the Moon at any given time. The separation of the ring modules was chosen to be such that the maximum number of baselines, in this case 15, provides a uniformly resolved field in log(height)-space. Fig. 5.5 shows the installed ATP on the roof of PEARL. The largest baseline is 2 m (distance from top-most to bottom-most ring module). Below the lowest ring module, the adapter module with all connections to the 30 cm long computer enclosure can be seen. In total the ATP is 2.4 m long. All ring modules are identical in design so that one spare unit can be used to replace any of the existing modules in case of a failure. A ring module is milled out of a single aluminum disk having an outside diameter of 8” (203.2 mm). The apertures are milled from the outside of the ring and windows seal the module. This general design has been used to minimize
Figure 5.5: The ATP on the roof at PEARL is seen on the right panel. To test its operational readiness for the remote sites, the computer and storage devices are located in the can just below the lowest ring module, seen on the left panel. Five of the 8 windows, glued into the golden frames with the sharp aperture stop are fully or partly visible. On the right panel on top of the ATP the weather station is mounted, employing a temperature/humidity sensor, a pressure sensor, a deicing sensor and an Iridium antenna for remote communications.

the number of protrusions and edges on the outside, providing a smooth outer surface to reduce rime ice accumulation. To prevent icing, each window is coated with an electrically conducting Indium-Tin Oxide (ITO) layer (CEC10B from Praezisions Glas & Optik GmbH), connected to computer-controlled power source. This coating has a flat transmission of 85% over the entire wavelength range from 700 nm to 1100 nm.
A longpass edge filter at 715 nm blocks the main auroral emission lines (Chernouss et al., 2005). In addition, we decided to also block the hydrogen Balmer lines, whose H_α-line on the long wavelength end is located at 656 nm. The Paschen series, radiating in the infrared longwards from 828 nm, is not considered to radiate at a significant level. The diode is located behind this filter and directly connected to a preamplifier board. The diodes are angled 27° to the horizontal, accounting for the fact that the minimum acceptable Moon altitude was chosen to be 18° in altitude. Taking into account the Moon’s maximum declination of around 26° and the 80° latitude of PEARL, the Moon’s maximum elevation is therefore 36°. The aperture stop, machined into the ring module, provides a vertical opening of 27°±9°.

While the Sun cycles between the fixed range from -23.5° to 23.5°, set by the Earth’s obliquity, the lunar declination range varies due to its orbital tilt of 5° to the ecliptic. So, the northernmost declination value cycles between 18.5° and 28.5°. The period of this variation, the motion of nodes of the Moon’s orbit with the ecliptic, is 18.6 years and is caused by lunar precession. Not only must the Moon be high in the sky, but also, the Moon must be within ~8 days of full. Only during this period does the ATP operate.

Fortunately, the current Moon orbit has the full Moon favorably placed, coinciding with its northernmost position in the sky. The highest declination of the full Moon occurred in 2006. Presently, the Moon is still high in the sky and the measurements are possible. Also, the full Moon reaches the northernmost declination in winter, when the sun is farthest south. For the period 2013-2017, the time for the moon being in the accessible altitude range is minimal and seeing measurements in the High Arctic are only possible within a few days of the full moon, as the Moon does not reach sufficient altitude otherwise. Fig. 5.6 shows the daily path of the Moon on November 4th 2009, one of the first nights when we obtained data. Its highest declination was at that day around 24°, corresponding to an altitude of 34°.
Figure 5.6: Moon’s path on the sky on November 4th 2009 as seen from PEARL (latitude=80.05352°N, longitude=86.41652°W) with the Moon position indicated at midnight. The Moon reaches a maximum elevation of ≈34° and stays about 20 hours above 19° in elevation, the lower detection limit. At the displayed night, the moon’s elongation was 161°, about one day after full Moon. Data were taken ~3 hours before the displayed local midnight configuration over a 2 hour period between an azimuthal range from ≈135° - 165°, then at local 5 h for 2 hours (azimuthal range ~260° - 290°) and finally over a one hour period to the east at local 19 h (azimuthal range ~90° - 105°). The graphical display is taken from the online applet Sun & Moon Polar, from J.Giesen, www.GeoAstro.de, with permission.
5.2.3 Detailed Design of the ATP

5.2.3.1 Ring module design

8 photodiode sensors are arranged in each ring module such that they subtend an angle of 36° to each other. As the path of the Moon does not reach the lower detection limit to the north, the region ±36° from north is not observed. With the Earth’s rotation, the Moon passes from one diode to the adjacent ~140 minutes. To ensure proper hand-off between subsequent diodes, their fields of view overlap horizontally by 1°, resulting in a horizontal aperture stop of 41° per diode. This is the unvignetted field of view and takes the extent of the diode area into consideration. The aperture windows are first coated with antireflecting coating and then ITO has been overcoated. Wires are bonded on each side face of the window, using the cold solder material silver epoxy. Each window is then glued into the aluminum frame with a silicon-based adhesive. This material withstands -50°C, is water resistant and electrically non-conductive. In addition it does not conduct heat easily, so the applied energy stays on the window. The inner side of the frames serves as the aperture stop. Fig. 5.7 shows the design of the ring module and in Fig. 5.8, the interior of the ATP can be reviewed schematically. Four openings on the top of each ring module, seen on the left panel of Fig. 5.7, host sealed connectors for electrical feed-throughs (LEMO). These provide electrical power to the window heaters and photo diodes as well as the addressing lines. The signal connection is also incorporated. The interior of the ring module hosts the ring board, whose multiplexer is used as analog switch to only provide power to the diodes in the sector that sees the Moon. The respective signal is preamplified by a low-noise FET operational amplifier employing a 100MΩ feedback resistor and conditioned subsequently with a 233 Hz electronic bandpass filter before being sent to the computer in the bottom part of the ATP. With a sampling rate of 800 Hz, the Nyquist frequency is 400 Hz and to prevent aliasing, the signal needed to be attenuated before this limit. With off-the-shelf components, the bandpass of 233 Hz
Figure 5.7: Ring module 3D rendering with golden frames. The left panel shows the view into one aperture. The blue nitrogen filling/venting valves are also visible. The openings for the electrical feed-through connections are in the back. The right panel shows the lower side of the ring module, to give a view of the interior. Each diode section has a round opening to host the auroral filter. On the right side, the north side of the module with no windows is visible. At that location on the inside, space for the heater board is cut out. All electrical wiring is routed through the hollow center hole, so that no crucial wiring is directly exposed to the environment. The entire stack is also held together with a stainless steel cable, that connects the lid with the bottom piece and which is designed to be pulled in order to apply tension to the cable and hence strength to the ATP stack.

was chosen. A separate circuit board controls the heating of the windows and selects the window to be heated via analog switches. Only one column, hence a total of six windows – one for each ring module – is heated at any given time. The interior of the ring module is sealed and filled with dry argon at a pressure of 10 psi above atmospheric pressure. Two self-sealing valves are used for the filling and venting of argon.

Each ring module is electrically connected with the subsequent modules using daisy chain connections for the address and power lines. Only the six signal cables are routed from each ring module directly to the computer. Each ring module is separated by spacers that define the baselines (see Section 5.2.3.2). During operations, only the diode
The column, facing the Moon (called sector hereafter), is powered up.

The heaters use a separate 24 V power supply to provide more heating power as the current is limited by the resistance of the ITO-coated windows. These two power lines are electrically separated as they are connected to two separate boards in the ring module. They are also physically disconnected as they do not share the same line nor do
they share the same feed through. Fig. 5.9 shows the interior of the ring module with its preamplifier boards, the heater board and the ring board. Each window, with a coated area of $\sim 15 \text{ cm}^2$ (33 mm $\times$ 45 mm), provides a sheet resistance of $\sim 20 \, \Omega/\square$ (Ohm per square), hence with a 24 V potential, 1.2 A are drawn through each window and thus the setup provides about 30 W of heating power to each window. The ATP is vertically aligned and locator pins are used to ensure proper vertical and rotational alignment of the ring modules.

The computer enclosure is located below the stack of spacers and ring modules. Its diameter is the same as that of the spacers and the ring module. To ensure proper operation, the computer enclosure is also filled with dry argon and sealed. This requires an adapter module, which connects all wires from the ring modules to the computer.

Figure 5.9: The interior of a ring module with its preamplifiers and heater circuit boards is shown. On the left side, the single preamplifier boards are visible. On the lower side the heater board with its 8 red and black wires, guided through the internal circumference towards each window, is shown. In addition the four connectors are also visible. On the right panel, the attached ring board can be seen. Each preamplifier is connected to the board with its own 6-pin ribbon cable.
enclosure. Additionally, the ATP features its own weather station, attached to the topmost ring module and a lid. This includes a temperature/humidity sensor, a pressure sensor, an ice sensor and, for remote connections to a satellite, an Iridium antenna. Cables from these external devices are also connected to the adapter module from outside, as is the Ethernet connection, a redundant RS232 serial connection and the power cable, hosting a 12 V as well as the 24 V line. Thus the adapter module connects cables from inside as well as outside and routes all through hermetically sealed connectors to the computer enclosure below. The computer enclosure hosts a rugged, low-power single board computer (SBC) (TS-7260 from Technologic Systems, PC-104 format), the analog to digital converter (ADC) board, the FPGA board, the Iridium modem, the power distribution board as well as the ice sensor control board. The FPGA board is used to put the digital signals from the ring modules, as well as the weather station data, into programmed memory regions. Fig. 5.10 shows the interior of the computer enclosure on the two right panels, as well as the adapter module on the left side. The adapter module only shows connected wiring for the external devices, with the internal connectors being open and visible. One storage device, a 64 GB USB memory stick, has been located outside to allow easier recovery of data in the field. A 32 GB SD-card is located on the SBC to provide more storage. The SBC runs an embedded linux operational system, which is a light version of the Debian linux distribution, modified for low-power applications. In low-speed mode, the entire SBC uses less than 0.25 W.

5.2.3.2 General Mechanical Design Aspects

The separation between each ring module has been chosen to make the distribution of logarithms of the separation of each diode pair as uniform as possible. The minimum baseline is limited to 80 mm, the width of one ring module, Table 5.1 shows the photodiode locations.
Chapter 5. Design and Operations of Lunar Scintillometers

Figure 5.10: The external and internal view of the ATP computer enclosure is shown. Adapter module is visible on the left panel with external wiring from weather sensors, RS232 connection, ethernet connection and power connection as well as the USB stick. The middle panel shows the power distribution board as well as the wiring from each connector of the adapter module on the top. On the bottom of the middle panel, the ice sensor control board sticks up and behind the ribbon cables, a part of the iridium modem is visible. The backside of the computer enclosure is shown on the right panel. The FPGA board is stacked on the red single board computer. It is rated to $-60^\circ$C and features very low power consumption. Connected to the FPGA board on the lower side is the ADC board with its six connectors at the bottom, connecting the signal from each ring module separately. The multiplexing unit in the ring module has already chosen the signal from the correct window within one ring module, sent it through the bandpass filter and then to this board for digitisation.

This results in 15 baselines with relative separations shown in Table 5.2. The distribution of baselines in logarithmic space is displayed in Fig. 5.11.

5.2.3.3 Spectral Response of the ATP

For the design of the preamplifier, the spectral response of the detector system had to be estimated. The solar spectral energy distribution (SED) was assumed to be a black body at a temperature of 5800 K, described by the Planck function. Transforming the
Table 5.1: Location for each ring module of the ATP, as measured from the top

<table>
<thead>
<tr>
<th>Number</th>
<th>Position [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>395</td>
</tr>
<tr>
<td>3</td>
<td>593</td>
</tr>
<tr>
<td>4</td>
<td>721</td>
</tr>
<tr>
<td>5</td>
<td>877</td>
</tr>
<tr>
<td>6</td>
<td>2000</td>
</tr>
</tbody>
</table>

Figure 5.11: Differences in the logarithm of separations for all baseline pairs of the ATP. These have been chosen to be as uniform as possible.

flux with the inverse square law to the Earth location, multiplying by $4\pi$ to account for radiation from all directions and integrating over the relevant wavelength range from 250 nm to 1100 nm gives a solar flux of 1050 W/m$^2$. Extending the wavelength range to infinity gives the well-known solar constant of 1350 W/m$^2$. In order to estimate the
Table 5.2: Individual baselines separations of the ATP.

<table>
<thead>
<tr>
<th>Ring number pair</th>
<th>relative separation [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4</td>
<td>128</td>
</tr>
<tr>
<td>4-5</td>
<td>156</td>
</tr>
<tr>
<td>2-3</td>
<td>198</td>
</tr>
<tr>
<td>5-3</td>
<td>285</td>
</tr>
<tr>
<td>2-4</td>
<td>326</td>
</tr>
<tr>
<td>1-2</td>
<td>395</td>
</tr>
<tr>
<td>2-5</td>
<td>482</td>
</tr>
<tr>
<td>1-3</td>
<td>593</td>
</tr>
<tr>
<td>1-4</td>
<td>721</td>
</tr>
<tr>
<td>1-5</td>
<td>877</td>
</tr>
<tr>
<td>5-6</td>
<td>1123</td>
</tr>
<tr>
<td>4-6</td>
<td>1279</td>
</tr>
<tr>
<td>3-6</td>
<td>1407</td>
</tr>
<tr>
<td>2-6</td>
<td>1605</td>
</tr>
<tr>
<td>1-6</td>
<td>2000</td>
</tr>
</tbody>
</table>

diode’s response to moonlight, the SED was multiplied by the Moon’s albedo (Shkuratov et al., 1999) and the quantum efficiency of the diode. Hamamatsu’s S1336-BK diode has a 5.8 mm×5.8 mm effective area and its sensitivity is given in A/W. Multiplying this by $hc/\lambda q$, with $h$ being Planck’s constant, $c$ the speed of light and $q$ the elementary charge, gives the quantum efficiency of the device. Only wavelengths longer than 715 nm are detected. Fig. 5.12 shows the individual contributions and the final spectral response of a single ATP sensor.
Figure 5.12: Spectral response of the detector unit of the ATP, with all contributions, starting with the solar spectral energy distribution (SED) (divided by 10, for display purposes), the moon’s albedo, diode quantum efficiency and edge filter.

5.2.3.4 Peripheral Equipment – Weather Sensors

Even though at the current ATP location at PEARL a weather station is in place, the ATP is equipped with a temperature, humidity, pressure and an ice sensor. This enables the ATP to be operational independently in a remote location without supporting infrastructure, and still be able to record basic weather information, which is very useful in interpreting the recorded scintillometer data. The ice sensor will be used to turn on and off heating and will play a crucial role when remotely deployed and battery power is limited.

In addition, an Iridium modem with an Iridium antenna is installed to allow for communication of basic house keeping information during remote operations. Also, updated operations software may be transmitted this way. At the present location at PEARL, these options are only used for testing purposes.
5.2.3.5 Communication and Operation of the ATP

Communication with the ATP is provided via ethernet from the local area network at PEARL. A C-program, written by P. Hickson, compiled at UBC and sent via ssh to the SBC computer, performs all operational tasks. This includes calculating Moon position, deciding if all observation requirements are met, and then commanding the electronics to power the correct diode sector and acquire Moon intensity signals. In the future, this program will perform daily or weekly calls home via satellite, check if heating is required and check the ATP’s status by evaluating information from all weather and internal sensors.

5.2.3.6 Power Consumption of the ATP

As described in previous sections, the ATP is designed for remote deployment and as such low power consumption. The only large power consumption is dedicated to the window heaters. The following table shows the consumption of the single components, apart from the window heater system.

<table>
<thead>
<tr>
<th>Device</th>
<th>Number of devices</th>
<th>Power in single device [mW]</th>
<th>Total Power [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>All electronics in one ring module</td>
<td>6</td>
<td>67</td>
<td>401</td>
</tr>
<tr>
<td>ADC board</td>
<td>1</td>
<td>197</td>
<td>197</td>
</tr>
<tr>
<td>SBC TS-7260</td>
<td>1</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>Pressure sensor</td>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Temp/RH sensor</td>
<td>1</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Iridium modem during data transfer</td>
<td>1</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>Ice sensor with no heating</td>
<td>1</td>
<td>~500</td>
<td>~500</td>
</tr>
</tbody>
</table>
5.3 Design and Operations of the PTP at CFHT on Mauna Kea, Hawaii

5.3.1 PTP Design

The PTP consists of several parts that are assembled manually before observing begins. Fig. 5.13 shows the PTP in the lab on its tracking mount. The 8 diodes with small baffles are located along the bar. The data acquisition computer is located below the tripod. During the design of the PTP, P. Hickson thought about measuring wind speed and velocities through time covariances of the signal, and hence the PTP was designed to be used in a linear as well as a right angle configuration. At the moment it is only
used in the linear configuration and I will therefore focus on this configuration. The separations of the PTP are chosen by analyzing the difference in logarithmic baselines and making its distribution as flat as possible. Each design configuration was hereby given the same weight. Table 5.4 shows the used adopted distances from one end of the linear bar. The design of the PTP followed closely that of the ATP. The preamplifier electronics are identical and the 715 nm edge filter and the photo diode are the same as used in the ATP design. Thus the spectral response to moonlight is identical.

5.3.1.1 iOptron mount and Tripod

The PTP is mounted on a commercial amateur astronomy alt-azimuth mount, the Minitower from iOptron. A hand paddle is used to control its motion. The mount can operate using battery power or an A/C power supply. An internal GPS receiver determines its current position, even inside the CFHT dome.

Table 5.4: Location for each diode of the PTP

<table>
<thead>
<tr>
<th>Number</th>
<th>position [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>59</td>
</tr>
<tr>
<td>3</td>
<td>529</td>
</tr>
<tr>
<td>4</td>
<td>647</td>
</tr>
<tr>
<td>5</td>
<td>1294</td>
</tr>
<tr>
<td>6</td>
<td>1529</td>
</tr>
<tr>
<td>7</td>
<td>1706</td>
</tr>
<tr>
<td>8</td>
<td>2000</td>
</tr>
</tbody>
</table>
5.3.1.2 Bar with Photodiode Units and Finder Scope

The photo diodes are located on a 2 m long bar (1.5" square extruded anodized aluminum). Each unit is connected with a power and a signal cable (BNC-SMB connectors). These cables are secured to the bar with cable ties and do not need to be removed. The signal coaxial cables are connected to the data acquisition computer. Near the mount a finder scope is located to help with the initial alignment of the Moon and with subsequent pointing checks.

5.3.1.3 Data Acquisition Computer

The amplified signal from the photodiodes are digitized by a National Instruments data acquisition computer using an 8 channel 24 bit ADC card (NI PXI-4472). DC-signals are digitized directly with no filtering. This computer runs Windows XP with Labview SignalExpress being the acquisition program.

A control program was written in the Labview SignalExpress environment from P. Hickson and extended by me. Fig. 5.14 shows the display with 8 graphs of the photodiode signals to allow for real time validation of the signal levels, important especially for inside measurements where moving dome slit or other parts in the dome may shadow some photodiodes.

5.3.2 PTP Data Acquisition Summary

The PTP is routinely deployed whenever the Moon is within on week of full Moon. If CFHT operations allow, data are taken from inside the dome through the open dome slit if a direct line of sight to the Moon is available. If not, the PTP is taken outside and data are taken from near the MKAM tower. Regular data acquisition began in mid-May and to date ~220 hours of outside data and ~37 hours of data from inside the dome are recorded. Fig. 5.15 shows the hours of data acquisition, both inside and
outside, and Fig. 5.16 shows the same, separated for inside and outside observing. For the analysis, \( \sim 80\% \) (172 h) of the outside data and \( \sim 55\% \) (21 h) from the inside data were used. The rest has shadowed diodes or shows other contamination that makes it unreliable. Data from inside the dome often showed shadow motion on some diodes as well as unusual spikes in the seeing data. Absolutely photometric nights are required. For useful data with the PTP, the Moon should be at least 10\(^\circ\) in altitude. After these cuts, the subset, shown in Figure 5.16 of data has been used for subsequent analysis. Table C.1 in Appendix C lists every individual night and a short description of the PTP location for that night. If the instrument was located at different locations more than
**Figure 5.15:** Total data acquisition summary for the PTP on Mauna Kea

**Figure 5.16:** Data acquisition summary for the PTP on Mauna Kea for recorded data from inside (left panel) the CFHT dome, as well as outside near the MKAM tower (right panel) one entry per night is given.
Figure 5.17: Data acquisition summary for the PTP on Mauna Kea for recorded and cleaned data from inside (left panel) the CFHT dome as well as outside near the MKAM tower (right panel).
Chapter 6

Ground Layer Seeing Results from the Canadian High Arctic

6.1 Ground Layer Seeing in the Canadian High Arctic

The potential of the Canadian High Arctic as a possible site for astronomical observatories in optical and infrared wavelengths was introduced in Chapter 3. This section discusses in more detail the overall site test campaign (Steinbring et al., 2010), and then presents results of our ground layer turbulence measurements.

Since summer 2006, a team lead by E. Steinbring (HIA) and R. Carlberg (U of T) has conducted site testing on selected mountain tops at the northwest side of Ellesmere Island (Steinbring et al., 2008). The motivation is that the Arctic is comparable to the Antarctic in many ways, but includes mountainous terrain, which would enable construction of observatories above any strong surface layer, the main contributor to seeing for the flat topographic environment around Dome C in the Antarctic (Agabi et al., 2006). The Arctic is very cold and dry (Lesins et al., 2010), which reduces thermal background and absorption in the infrared. In this desert environment, the precipitable water vapor is \( \sim 1 \text{ mm} \) for the winter months at 1500 m elevation, as shown in Fig. 6.1 (Ivanescu, 2010). This compares to the Atacama Large Millimeter Array (ALMA) site in northern Chile, which has 1.5 mm (Wilson, 2008). Cloud coverage is the next important factor. In a first attempt, data from the MODerate resolution Imaging Spectrometer
Chapter 6. Ground Layer Seeing Results from the Canadian High Arctic

Figure 6.1: Median precipitable water vapour in Eureka from 1994 to 2007 from radiosonde data (Ivanescu, 2010). The dotted lines show the annual variability, and hence are an indicator of the uncertainty.

(MODIS) on board the Terra and Aqua satellites, taken in 36 spectral channels, has been used together with an improved analysis software (Liu et al., 2004b) to obtain nighttime cloud coverage at 1-km resolution. Distinguishing between snow or ice-covered mountain peaks and clouds is a difficult task. Nevertheless, the assessment showed good conditions around the NW coast of Ellesmere Island as well as some less preferred inland locations. Ellesmere Island has two permanently manned facilities, the Environment Canada weather station site in Eureka at 80°N (not on the map in Fig. 6.2) and the Department of National Defense (DND) site in Alert at 82.5°N, 62.3°W on the East coast of Ellesmere Island, both of which have taken weather data over the last 50 years. However, these sites are both located at sea level. The atmosphere is usually completely
decoupled at the top of the inversion layer, and hence remote measurements above the inversion layer are required to get the full picture. Surface measurements of wind are affected mostly by surface friction and therefore reflect mostly local weather patterns rather than contributing to an understanding of the large-scale weather pattern. On large scales, the weather is dominated by global phenomena like the Hadley cell circulation, which creates easterly winds in the Arctic and the mid-atmospheric polar vortex that is usually rotating counter-clockwise, hence producing westerly winds. This global arctic weather pattern is readily studied by remote optical and radio measurements from the facilities in Eureka and Alert. However it remains to be seen what the local weather at specific mountaintops is like. The 1-km satellite resolution of cloud cover needs to
be validated with direct all-sky or horizon cameras from such locations. As well, the
stability and location of the inversion layer throughout the winter needs to be analyzed
with local weather data.

Therefore, weather data were acquired from three pre-selected mountain tops near
the NW coast of Ellesmere Island starting in 2006 with the deployment of two weather
stations and a third followed during 2007 (Steinbring et al., 2008). Air temperature,
relative humidity, wind speed and wind direction were recorded by a weather station.
Satellite connection was established to provide communication. In addition, a horizon
camera measured the cloud coverage. A wind generator and batteries provide power.

In the following years, the team gained experience in the harsh arctic environment and
added an all-sky camera and a Polaris tracker. Because these cameras use more power, a
methane-driven fuel cell was deployed, but was found to be unreliable (Steinbring et al.,
2010).

Weather data from a three year period revealed generally calm and attractive con-
ditions. With this reassurance the next step was to measure astronomical seeing. For
this purpose, P. Hickson and I designed the ATP for ground layer (GL) turbulence
measurements. As in the Antarctic, the GL is believed to be the main contributor to
seeing in the Arctic. The absence of a jet stream at these high latitudes should lead to
a low free-atmospheric contribution to the seeing, as found in the Antarctic (Lawrence
et al., 2004).

6.2 Observations and Results

The ATP was installed in September 2009 and regular data acquisition started in early
November after a commissioning phase in October. The harsh environment frosted the
ATP windows and the heating proved less efficient than we had hoped. It was concluded
that significant heat was being transferred to the aluminum housing, which acts as a
strong heat sink. Fortunately, the PEARL technician was able to use methanol and a brush to remove the frost and ice. Because of the frost, not many hours were obtained in November, but anticipation was high to get data in December. However, a week of 80 to 170 km/h winds weakened the 3/16” stainless steel cable that holds the instrument together. A severe storm on November 26th 2009 broke the cable, resulting in severe damage to the ATP. We were able to repair the damaged parts with an improved more rugged steel cable and the ATP was reinstalled in January. While such a storm is not unusual, the length over one week is rare according to the technicians from PEARL. With the change of a better strengthening cable, the ATP should now be well equipped to withstand such weather. The February lunar cycle was always plagued by thin cirrus clouds and hence only in March 2010 were we able to collect some data. The Sun was never far below the horizon. This is the reason why at the time of writing, only 752 minutes of data have been obtained (388 minutes in November and 364 minutes in March). Nevertheless, these data were obtained on 7 different days under a wide range of meteorological conditions, as well as in two seasons. We hope to acquire more data in the winter 2010-2011. Results obtained so far are summarized below. The data reduction and analysis software were done by P. Hickson.

Data were obtained on November 4th and 5th 2009 and over four nights at the end of March 2010. While November showed spectacular seeing conditions, the March data set showed diversity in conditions, which are reflected in the final seeing results. As an example, the worst seeing conditions are shown in Fig. 6.3 (right panel). For comparison very good seeing conditions are shown on the left from November data. This is a subset of the data. The wind came from NW directions for this data subset, shown in Figure 6.3 on the right, and the relatively flat topography in this direction suggests that a strong boundary layer had developed by the time the air reached the ATP.

For the total data set, a cumulative distribution for the estimated GL seeing and an assumed free atmosphere contribution seeing was calculated. The ATP is only sensitive
Figure 6.3: Ground layer seeing derived from two nights in winter 2009. While good seeing conditions are shown on the left side (Nov. 4th 2009), the right panel shows a 2-hour section from Mar. 23rd 2010 with worse seeing conditions. The y-axis is the zenith corrected FWHM of a seeing disk at 500 nm, from Hickson et al. (2010).

to GL turbulence, and hence the free atmosphere (FA) component has to be estimated from Antarctic balloon measurements (Agabi et al., 2006). It was assumed to follow a log-normal distribution with 0.25” mean and 0.25” standard deviation (Racine, 2010, private communication). Fig. 6.4 shows the estimated total seeing through the full atmosphere for a telescope at the indicated heights. In summary, Table 6.1 shows the quartile seeing results, for the GL only (left side) and the total atmosphere. These preliminary results suggest that, above 10 m, the median total seeing at PEARL is better than 0.5”. This is lower than values measured anywhere on Earth (Schöck et al., 2009).

As already stated in Section 3.3 a lunar scintillometer does not need to be calibrated as it measures directly normalized intensity, whose fluctuations are used to derive the covariance function. It is therefore very robust and less affected by systematics than a DIMM, for example. Confidence in these results is strengthened by data obtained at Mauna Kea with the PTP, which is a very similar instrument. In Section 7.2 results from the PTP are summarized, and in Appendix D several example nights with PTP data and comparison with MKAM DIMM data are given. A mean turbulence profile
Figure 6.4: Cumulative distribution of total seeing, estimated from all ATP data obtained to date. A free atmospheric component was determined by random draws from a log-normal seeing distribution having a standard deviation of 0.25 and mean value of 0.25 arcsec, from Hickson et al. (2010).

Table 6.1: Summary of seeing statistics.

<table>
<thead>
<tr>
<th>Height</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 m</td>
<td>0.246</td>
<td>0.390</td>
<td>0.564</td>
<td>0.383</td>
<td>0.496</td>
<td>0.649</td>
</tr>
<tr>
<td>20 m</td>
<td>0.178</td>
<td>0.274</td>
<td>0.427</td>
<td>0.325</td>
<td>0.413</td>
<td>0.591</td>
</tr>
<tr>
<td>50 m</td>
<td>0.093</td>
<td>0.158</td>
<td>0.220</td>
<td>0.268</td>
<td>0.320</td>
<td>0.388</td>
</tr>
<tr>
<td>100 m</td>
<td>0.068</td>
<td>0.106</td>
<td>0.146</td>
<td>0.244</td>
<td>0.287</td>
<td>0.337</td>
</tr>
</tbody>
</table>

of the ground layer for Mauna Kea, compared to a mean turbulence profile from the Arctic is shown in Figure 6.5. As also stated in Section 7.2 and shown in Fig. 7.3, this is a typical GL profile shape on Mauna Kea, and that specific night shown was also exceptionally good on Mauna Kea. This sharp rise in turbulence below 20 m is not seen
in the Arctic data. Considering a free atmospheric component on Mauna Kea of 0.33″

Figure 6.5: Mean ground-layer seeing as a function of height, obtained using similar lunar scintillometers at Mauna Kea and at PEARL. The data are from just one night in each case, but were obtained during typical wind conditions at both sites. The dotted lines indicate the standard error of the mean.

(Skidmore et al. 2009), compared to that in the Antarctic of 0.25″ as measured for Dome C (Agabi et al. 2006), and a weaker GL, we conclude that the seeing, we observed in the Arctic is exceptional. This will be investigated in the future and validated (or rejected) with more data.
Chapter 7

Ground Layer Seeing Results from CTIO in Chile and Mauna Kea, Hawaii

7.1 Seeing Measurements and Statistics from 3 Years of Data at CTIO

Over the last three years, more than 700 nights of data have been accumulated from the CTP on Cerro Tololo at CTIO. Data analysis is still in progress. An initial result is that the annual median seeing in the ground layer seems to get slightly weaker every year (Gagné, 2010). Fig. 7.1 shows a time variation of $C_N^2$-profiles for the first 500 m over one night in February 2007. The instrument resolves small turbulent cells and their time evolution. Thus, local seeing variations can be linked to the source in the atmosphere. To estimate the seeing over the total atmosphere, a free atmosphere component that depends in mid-latitudes on the jet stream condition and location, has to be added (Els et al., 2009a, Schöck et al., 2009). Over the years 2004 to 2008, Els et al. (2009a) recorded seeing data on Cerro Tololo, and estimates an integrated median GL seeing of 0.44”, derived from the subtraction of DIMM and MASS seeing (Els et al., 2009a). They do not report annual median seeing and its evolution and it will be interesting to compare
their annual results with ours, especially with the 1.5 year overlap in data acquisition.

7.2 Mauna Kea Ground Layer Seeing

In this section, general results are presented based on preliminary data analysis. Data from inside the dome and outside are strictly separated and because of the limited number of hours from inside, only very preliminary statements can be made. Outside, the number of hours is 5 times greater and hence a more thorough analysis is made. The analysis was done by me, using P. Hickson’s data reduction pipeline.

7.2.1 General Median GL Seeing Results from Inside and Outside

Fig. 7.2 shows a summary of GL seeing for all outdoor and indoor data. For comparison, the cumulative distribution of total seeing, as detected by the MKAM DIMM instrument,
as well as by the CFHT dome DIMM, for the time ranges when PTP data are available, are shown. The CFHT dome DIMM is an instrument, located inside the slit. Above 6 m from the instrument, the outside median GL seeing is 0.48"±0.01". This compares with the results from Chun et al. (2009), who find 0.51" as median seeing value in the GL. Their SLODAR/LOLAS measurements suffered from telescope turbulence systematics, which might explain the slight discrepancy. Also their data acquisition spans over an 18 month period, while the PTP data was mostly recorded in 4 months. The PTP does not detect any free atmosphere turbulence, and hence while the data from the scintillometer only shows GL contribution, the other two instruments show integrated seeing. The strength of the PTP is that it resolves the GL and hence from these summary plots it can be seen that strongest contributions arise from the region between 6 m and 50 m. In addition the dome DIMM instrument usually detects turbulence through a very turbulent skin layer surrounding the CFHT dome and hence it is not expected that the PTP inside data should follow its seeing values. With the PTP mostly located on the telescope floor, the line of sight to the moon passes nearly perpendicular through this layer while the line of sight of the dome DIMM generally subtends a larger distance in the strong turbulent region (private communication with R. Racine, 2010).

The indicated error estimates $\varepsilon_{\text{PTP}}$ on the median needs further explanation and the following formula was used:

$$
\varepsilon_{\text{PTP}} = \sqrt{\left[ \frac{1}{N} \sum_{i=1}^{N} \left( \hat{\varepsilon}_{\text{med},i} - \bar{\varepsilon}_{\text{med}} \right)^2 \right] + \varepsilon_{\text{sys},j}^2},
$$

(7.1)

with

$$
\bar{\varepsilon}_{\text{med}} = \frac{1}{N} \sum_{i=1}^{N} \hat{\varepsilon}_{\text{med},i}.
$$

(7.2)

The first term in the square root describes the standard deviation of $N$ bootstrapped median seeing values $\hat{\varepsilon}_{\text{med},i}$ with the mean $\bar{\varepsilon}_{\text{med}}$ and the second term describes a systematic
Figure 7.2: Cumulative distribution plots of ground layer (GL) seeing for all nights together, separated for INDOOR (left panels) and OUTDOOR (right panels) data. While the top two panels summarize GL seeing for heights BELOW the indicated values, the lower row is the summary for GL seeing ABOVE the indicated height. In the second row, the MKAM DIMM data as well as the CFHT dome DIMM data are shown in addition. Values are only taken when PTP data were taken, and separated for indoor and outdoor observation times.

error that accounts for different conditions depending where the instrument is located ($j = $indoor or outdoor). Both error terms are not correlated, and hence added in quadrature. For each bootstrap cycle $i$, a median seeing value $\varepsilon_{\text{med},i}$ is derived. To
account for random errors in lunar scintillometers, Tokovinin (2010) found between UBC’s CTP and his LuSci a random scatter rms difference of 0.3 on a log-log comparison plot of $C_N^2$ (see also Fig. 3.9). We assume the scatter to be log-normal distributed. Thus, instead of using $\epsilon_{med,i}$ directly, a random seeing value $\hat{\epsilon}_{med,i}$, drawn from a log normal distribution with mean $\epsilon_{med,i}$ and width $\epsilon_{med,i} \cdot 10^{0.3 \cdot 0.6}$, is taken. The factor $10^{0.3 \cdot 0.6}$ results from the power law dependence of the seeing and $C_N^2$ with index 0.6 (see Eqns. 2.5 and 2.6) and the rms difference of 0.3 in log space. This takes into effect the random measurement error and an estimate of the systematics for outside data, whose sources are described in Section 3.3. Given the fact that the CTP uses different electronics than the PTP, we add $\epsilon_{sys,\text{outdoor}} = 0.002''$ systematic error in quadrature to account for unknown differences between the two instruments CTP and PTP. For inside data this systematic error is $\epsilon_{sys,\text{indoor}} = 0.005''$ and also added in quadrature to take the increased inside noise sources into account. Even though great care has been taken to identify contaminated data, especially for data taken from inside, this additional error should be a fair estimate. For the MKAM DIMM data, a general systematic error of 0.02'', was determined by the extensive site-test campaign for the TMT (Skidmore et al., 2009), which uses the same setup and DIMM telescopes. For the dome DIMM, the systematic influences are unknown, but as it is probing through the telescope skin layer in different directions and hence different thicknesses, the systematic error is expected to be higher than for the unperturbed MKAM DIMM. We will now compare data taken from inside and outside. Care is needed due to the different number of total useful acquisition hours (20 h inside and 170 h outside – Section 5.3.2). It is unlikely that the same median conditions occurred for both data sets. In addition, the inside data are not evenly distributed over many nights, but on December 2nd 2009, almost 5 hours of inside data are useful (see Fig. 5.17). From the “below”-data (upper row panels in Fig. 7.2) it is interesting to note that the first 20 m show almost identical median seeing values (within errors, indicated in Figure 7.2). Inside data are primarily taken with the dome facing either
west or east, because the slit changes its azimuthal position fast while facing towards southern directions. So, inside data is biased towards directions with more favorable local conditions, as indicated in the detailed analysis of the outside data (Section 7.2.3). From the median GL seeing values one can extract the contribution from the range between 6 m and 20 m using Eqs. 2.5 and 2.6

\[
\varepsilon_{6m-20m} = \left[ \varepsilon_{<20m}^{5/3} - \varepsilon_{<6m}^{5/3} \right]^{3/5} \leftrightarrow \left[ \varepsilon_{>6m}^{5/3} - \varepsilon_{>20m}^{5/3} \right]^{3/5}, \tag{7.3}
\]

where the \( \leftrightarrow \) -sign means that from both median seeing descriptions “above” and “below”, the result could be derived; however some discrepancies exist. Taking Eqn. 7.3 for the outside data gives 0.25”\( \pm \)0.01” for the “below”-data and 0.27”\( \pm \)0.02” for the “above”-data, hence within errors they agree. Applying the same exercise for the inside data reveals 0.24”\( \pm \)0.02” for the “below”-data and 0.30”\( \pm \)0.06” for the “above”-data. Although the discrepancy for inside data seems quite large, it is still within the error margins. Of course such large errors have to be investigated and if possible reduced. It would be helpful to have a similar second lunar scintillometer inside the dome and compare the two data sets. This would reduce the systematic errors. Also an increased data set from inside will reduce the error significantly.

### 7.2.2 Median GL Seeing vs Height of Outside Data

From the upper right panel of Fig. 7.2 displaying the summary of outside data, it is clearly seen that Mauna Kea suffers from a substantial ground layer, even at the superior location of CFHT on the summit. Below 20 m, the median seeing contribution is 0.3”, and below 50 m this increases to 0.41”. This behavior is shown by a seeing vs. height diagram in Fig. 7.3 as an example. Fig. 7.3 shows how the extent of the boundary layer changes and with it the seeing contribution. Even with the data sample probing many different conditions on the summit, the general shape of the median seeing profiles stay
the same and seems to be a characteristic of Mauna Kea. This results confirms the result from Chun et al. (2009) that find the same characteristic, however with less spatial and temporal resolution. It is interesting that their measurements were carried out further up the ridge on the roof of the UH-2.2m dome on Mauna Kea.

Even the very best 2 hour period on July 20th (Fig. 7.4), with a GL median seeing above 6 m of 0.19" and a MKAM DIMM median seeing of 0.40", shows the same signature of a strongly-rising seeing contribution towards the ground. The lowest two panels show an interesting result. While the best ground layer seeing was determined for the night of July 3rd (lowest panel), the DIMM data suggest a better overall seeing value for the night of June 4th (second lowest panel). The almost identical values for the median seeing as measured by the PTP and the DIMM on June 4th suggest an exceptional low free atmospheric contribution. The full characteristics, for some example observing nights, are shown in Appendix D where $C_n^2$-profile maps are displayed together with seeing time series and cumulative distribution plots. Meteorological data help to identify possible reasons of seeing characteristics.

7.2.3 Median GL Seeing Separated by Wind and Cardinal Direction

From this discussion of the general shape and behavior of the boundary layer, it becomes clear that the data should be separated further into portions when the dome (for inside data) was facing into the wind ($\pm 45^\circ$), hence the PTP probes the free stream and wind flushes the dome through the slit, and times when the PTP probes the wake if the dome points away from the wind ($\pm 45^\circ$). A third portion is created for the time when the wind was perpendicular to the dome slit ($\pm 45^\circ$ on each side). The results are plotted in Fig. 7.5 for the “above”-data. In these plots the errors are not given due to readability reasons, but are similar to those given in Fig. 7.2.

For outside data the division was not taken to be the PTP facing into, or out of, the
wind, because too many obstacles are close by, which make such a comparison useless. However the wind direction with respect to the Gemini and CFHT observatory domes (both taken into one bin due to their N/S axis, compared to the outside PTP location near the MKAM tower) as well as wind from the east and west, seemed a better dividing rule.

Looking at the inside data of the “above”-plot in Fig. 7.5 interesting features are clearly visible. With the dome facing INTO the wind, the median GL seeing is exceptionally good. This is especially interesting because not only the median GL seeing outside the CFHT dome, hence > 20 m, shows such values but all inside data as well have weak turbulence contribution. It seems that blowing wind into the dome helps the dome venting and reduces the dome effect on local seeing. The data taken when the PTP was probing into the wake also supports this statement. Not only is the median GL seeing for heights >20 m and >50 m bad, but also inside the dome, values show severe degradation. The highest value indicating GL seeing above 100 m however does not show too much effect, which also supports the idea that this is a local effect, due to the dome wake and poor venting when the wind is not directly blowing into the open slit. The data for the perpendicular direction support the trends already shown for the other two cases. Additionally, the cumulative distribution plot for the “above”-data shows interesting features for the worse 40% of data. This does not show up in the median value but indicates that almost half of the time the turbulent wake of a perpendicular-directed wind affects the air volume throughout the ground layer. It has yet to be investigated what wind direction was responsible and if other observatory domes are causing such strong degradation. More data is hereby necessary. Fig. 7.6 shows for the perpendicular inside case that the upper GL is in fact responsible for that change in shape of the distribution function for the worst 40%. Interestingly, in the lowest 20 m not much difference is found between the “below”-data from inside for the case when the PTP faces into the wind and for the perpendicular case (0.19” to 0.22”). However for data <50 m,
the two median seeing values increase to 0.39", compared to 0.29". This indicates that the turbulent wake extends only in the 20 m to 50 m range just outside of the dome slit. The region between 50 m and 100 m on the other side does not show much difference any more. This is all consistent with the idea of turbulence being created by the round dome, which causes the laminar flow to detach and create turbulence around the dome. The depth of this turbulence might readily be determined if more inside data are taken and a more thorough wind analysis is possible.

For the inside data set, 5.5 hours of data were taken with the wind entering the dome, 4.5 hours with the wind opposite of the dome slit and 10 hours with the wind coming from perpendicular directions. Almost 0.75 hours of data were taken with the wind below 1.5 \( \text{m/s} \), hence in calm conditions.

For the outside data set, 102.7 hours of data were taken in easterly wind directions, 27.8 hours with westerly wind conditions and 21.8 hours with the wind coming from north/south directions over the two observatories. Almost 19.2 hours of data were taken with the wind below 1.5 \( \text{m/s} \), hence in calm conditions.

For the outside data, the upper panels in the second column of Figs. 7.6 and 7.5 show data with wind coming from easterly directions. The second row indicates data with westerly winds and the last row combines north/south direction, hence conditions with turbulence created by the Gemini dome as well as the CFHT dome. From the “above”-data it is obvious that the GL turbulence above 100 m is not affected, within the error, from local topography and buildings. Hence, the GL seeing >100 m is about the same for every wind direction. Comparing east and west directions show in the “below”-data, that the first 20 m are affected by about the same amount, with the current data set slightly favoring westerly wind directions over easterly ones. However, one has to take into account the uneven number of hours for these two datasets. The median seeing <20 m for the N/S-directions shows much more degradation and this shows the effect of the two domes. For the range between 20 m and 50 m, data with wind from east
show a median seeing contribution of 0.27”, while the data with westerly winds show a 0.24” contribution in the 20 m to 50 m range. Hence the same 0.03” - 0.04” difference as for the first 20 m. This is above the estimated error of 0.01”. This indicates a significant difference for the two preferred wind directions with local effects, however the small data set has to be considered and no strong statement is yet to be made. Both directions show For N/S directions, this seeing contribution from the 20 m to 50 m range is \(\sim 0.31”\) and hence stronger than for the E/W directions.

7.2.4 Median GL Seeing in Calm Conditions Inside and Outside

An interesting study is GL seeing in calm conditions, defined as wind speeds below 1.5 \(m/s\). Fig. 7.7 shows the respective cumulative distribution functions. As already stated above, for the inside data, only 3/4 of an hour of data was acquired so far in such conditions, hence all statements have to be regarded as preliminary. Outside data were taken for about 19 hours in comparison. Very striking is the comparison of the <20 m median seeing values from outside and inside. Inside the dome, the GL median seeing is almost doubled, which points again to a poorly vented dome. The median inside seeing in the first 20 m is 0.58”, while for the same conditions outside 0.32” is found! This dome contribution continues on even in the first meters outside the dome slit, which can be clearly seen by comparing the contribution in the 20 m to 50 m region from inside (\(~0.4”\)) to the outside data in the same range (0.2”). Not only is the dome poorly vented, but also heat from the telescope motors creates turbulence inside the dome, which is advected outside through the dome slit. In calm conditions, this creates a quasi steady-state turbulent environment.

This is an unfortunate situation, as the outside data suggest that calm conditions produce the best observing conditions in the ground layer above 6 m and higher. However with the CFHT dome situation, this very favorable situation is transferred into the most
unfavorable observing conditions. Calm conditions occurred during 10% of the useful PTP data acquisition time.
Figure 7.3: GL seeing (FWHM) in arcsec vs. zenith-corrected height. These plots indicate the GL contribution that a telescope would see if it is at that specific height. From the top panel to the bottom, the GL seeing gets better. For comparison, the MKAM DIMM total median seeing values for that night, calculated for the same time range the PTP got data, are given. The middle panel indicates an average night. All profiles are taken from outside data.
Figure 7.4: GL seeing (FWHM) in arcsec vs. zenith-corrected height. The best 2 hours of ground layer seeing on July 20th, 2010 for outside data. Median GL seeing above 6 m was 0.19", the median total seeing as estimated from the DIMM was 0.40".
Figure 7.5: Cumulative distribution plots of ground layer seeing for all nights for seeing ABOVE indicated heights, separated for INDOOR (left panels) and OUTDOOR (right panels) data. The different rows of panels indicate seeing for different wind directions with respect to the dome position (for indoor data) and with respect to the local obstacles (for outdoor data) like the CFHT or Gemini dome in the north/south-direction, or the open space towards the east or the west.
Figure 7.6: Cumulative distribution plots for all nights together for seeing BELOW indicated heights, separated for INDOOR (left panels) and OUTDOOR (right panels) data. The different rows of panels indicate seeing for different wind directions with respect to the dome position (for indoor data) and with respect to the local obstacles (for outdoor data) like the CFHT or Gemini dome in the N/S, or the open space towards the East the West.
Figure 7.7: Cumulative distribution plots for all calm wind conditions. Left and right columns of panels separate inside and outside data, whereas upper and lower rows of panels indicate GL seeing values below and above indicated heights, respectively. The “noisy” distributions for the inside data are a result of the small amount of data taken from inside in calm conditions.
Part III

Design/Operation and Results
from the UBC Lidar Experiment
Chapter 8

Lidar Design – High-Resolution Lidar Experiment for the Thirty Meter Telescope

8.1 Introduction

We describe the design of a new lidar experiment to investigate the spatio-temporal power spectra of the Na-variations at frequencies as high as 50 Hz. This system employs a 5 W pulsed laser and a 6 m liquid mirror telescope, which provide sufficient sensitivity for high-resolution studies. The transmitter is a Nd:YAG-pumped dye laser, with an optical collimation system that allows the beam divergence to be controlled over a range from diffraction-limited to several arcmin. This will also allow the investigation of saturation effects, important for the next generation high power LGS systems. Backscattered photons will be collected at the prime focus using four high-efficiency photomultiplier detectors and a fast counting system. The resulting system will provide vertical density profiles with a spatial resolution as small as 2 m.

1 A version of this chapter has been published as Pfrommer, T., Hickson, P., She, C.-Y., and Vance, J.D., ‘High-resolution Lidar Experiment for the Thirty Meter Telescope’ in the proceedings of the Society of Photographic Instrumentation Engineers (SPIE), Proc. SPIE, Vol. 7015, 70154Y (2008). The electronic version of this document offers fully hyperlinked cross-references throughout. We are grateful for support from Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), and the British Columbia Knowledge Development Fund (BCKDF).
Next-generation extremely large telescopes are being designed to achieve diffraction-limited image quality. To mitigate atmospheric distortions that prevent any telescope with diameter $D$ from achieving diffraction limited resolution $\theta \approx \lambda / D$, AO systems are employed. An AO system senses the phase distortion introduced by the atmosphere and corrects it by means of deformable mirrors. Since the atmospheric phase distortion changes on a short timescale, typically a few milliseconds, corrections must be made at several hundred Hz. The required phase information can be derived from light received by the telescope from one or more reference stars located near the object, or in the field of interest. However in most cases there are no stars of sufficient brightness available close enough to the object being observed (the “science target”). For this reason, the TMT AO systems will use artificial stars, created by illuminating the atmospheric sodium layer using a laser. These “laser guide stars” (LGS) are cylinders of resonant-fluorescent sodium atoms which, when seen from the telescope, appear star-like (or slightly elongated) with a minimum angular size, set by atmospheric turbulence, on the order of an arcsec.

A problem arises, however, because the sodium layer is extended in height. When seen from most points in the entrance pupil of the telescope (normally the primary mirror), the LGS appears elongated because of horizontal separation between the laser launch telescope and the observation point causes the cylinder of illuminated sodium atoms to be viewed obliquely. LGS elongation reduces the accuracy with which the centroid of the image can be determined, and also introduces systematic errors if the mean, intensity weighted, height of the sodium varies. Such changes can arise from fluctuations in the density distribution of sodium atoms within the layer or when new material is brought in from sublimating meteoroids.

A second problem arises because changes in the mean height of the sodium cause the LGS images to defocus slightly. The AO system cannot distinguish between defocus caused by the atmosphere and defocus caused by variations in the sodium mean height, making it impossible to keep the science target in focus. For this reason (and another:
LGS cannot sense atmospheric “tip-tilt” fluctuations that change the position of the science target) it is essential that NGS also be employed. The available stars are generally very faint, sufficient only to provide the lowest order phase information (tip-tilt and focus). Because of this, the focus signal is noisy and has insufficient time resolution to allow the AO system to distinguish perfectly between focus errors caused by the atmosphere and those caused by variations in the sodium height. Therefore, variations in the sodium height, if sufficiently large on small timescales, can cause a significant loss of performance of the AO system.

Initial estimates of the power spectrum of sodium height fluctuations have been made by Davis et al. (2006) who find that it is well represented by a power law, at least at frequencies below 3 mHz. Herriot et al. (2006) estimate that if this power spectrum continues to high frequencies it will contribute significant variance to the residual wavefront error of the TMT Narrow-Field Infrared Adaptive Optics System (NFIRAOS) (Ellerbroek et al., 2008). Because the extrapolation of the low-frequency power law over 6 orders of magnitude to frequencies as high as 1 kHz is highly uncertain, it is possible that sodium height fluctuations will not be a concern. But, it is also possible that they could pose a serious problem for AO systems of the TMT and other extremely large telescopes. For this reason it is essential to determine the temporal behaviour of the sodium density profile at higher frequencies, close to those of the atmospheric focus fluctuations. This is the primary aim of the LZT lidar project.

AO systems employing pulsed lasers have the potential to overcome some of the limitations imposed by the finite thickness of sodium layer. By tracking a pulse as it travels upward through the layer, the LGS position and focus can in principle be corrected continuously. Radial-format CCDs could shift photoelectrons rapidly to follow the transverse motion of the LGS as the laser pulse propagates upward, thus defeating LGS elongation. Dynamic refocusing can correct for the change in range to the LGS during propagation. In pulsed laser systems, the luminous energy is concentrated into
a pulse of short duration. The instantaneous energy density is thus much higher than in continuous wave (cw) systems. Because of this, and the need to focus the beam to reduce the angular divergence as much as possible, typically to an arcsecond or smaller, saturation of the sodium atoms becomes a potential issue. Saturation occurs when a large fraction of the sodium atoms are excited to the upper state of the transition by the laser photons, reducing the number of atoms in the ground state. Since the cross section for absorption of laser photons is proportional to the number of atoms in the ground state, the efficiency drops as many laser photons propagate upward without being absorbed. This limits the return flux from the LGS. This effect needs further study and analysis to quantify the potential impact on future TMT AO systems.

To address the above-mentioned issues, the main objectives for the UBC lidar system are:

- Measure the vertical density profile of the sodium layer with a temporal resolution of 50 Hz and a vertical resolution of 5 m or better.

- Determine the spatio-temporal power spectra of the density variations and assess the degree to which match-filtering type centroiding of elongated LGS can provide improved performance.

- Determine the temporal power spectrum of the mean (intensity weighted) height and assess the performance impact of these fluctuations on NFIRAOS.

- Model Na saturation effects and confirm the results by direct observations. (This is a secondary goal to support future TMT AO systems)

In the following sections, we will describe the design of a lidar system capable of detecting sodium-layer variations in the 50 Hz range as well all other outlined objectives.
8.2 Theory

8.2.1 Effect of Na-height Variations on Wavefront Error

Light propagating from a LGS at distance \( z \) along the line of sight produces spherical wavefronts with radius of curvature \( z \) reaching the telescope. When correctly focused, the telescope optics transmits this light to the LGS wavefront sensor (WFS) entrance pupil as a plane wave (assuming perfect optics and no atmospheric turbulence). If now the distance to the LGS changes by a small amount \( \Delta z \), with no refocusing, the wavefront arriving at the WFS acquires a small curvature. The rms optical path difference between this wavefront and the original plane wave (averaged over the pupil with the piston term removed) is given by [Davis et al. (2006)]

\[
\sigma_f = \frac{1}{16\sqrt{3}} \frac{D^2}{z^2} \Delta z.
\]  

(8.1)

The effect of this variation on the wavefront error of the science image produced by the AO system can be estimated as follows. Let \( P_\nu(\nu) \) be the temporal power spectrum of the mean height of the sodium and \( \zeta \) be the zenith angle of the LGS (\( z = h \sec \zeta \)). Let \( H_\nu(\nu) \) be the residual transfer function of the AO system to LGS focus errors. Then, the residual wavefront variance is given by

\[
\sigma_{fr}^2 = \frac{1}{768} \frac{D^4}{h^4 \sec^2 \zeta} \int_0^\infty |H_\nu(\nu)|^2 P_\nu(\nu) d\nu.
\]  

(8.2)

Davis et al. have estimated the power spectrum of mean height variations from data obtained with the Colorado State University (CSU) lidar system. This system has a sampling frequency of approximately 2 min and a vertical resolution of 150 m. Thus, it is possible to determine the power spectrum over a frequency range of 10 \( \mu \)Hz to 3 mHz. From an analysis of 28 nights of CSU lidar data, Davis et al. find the following functional
The above sodium power spectrum, they estimate a median residual rms wavefront error of 24 nm and a 90th percentile error of 63 nm, which is a significant portion of the overall error budget.

A major source of concern is the fact that the power spectrum was measured at frequencies below 3 mHz, yet the residual transfer function has most of its response above 10 Hz. The required extrapolation of the power spectrum over some four orders of magnitude in frequency is a significant source of uncertainty and risk. Direct measurements of the power spectrum at frequencies greater than 20 Hz will help to mitigate this problem.

8.2.2 Lidar Basics

A sodium lidar uses a pulsed laser to excite the Na D\textsubscript{2} resonance hyperfine transition at 589 nm ($^2P_{\frac{3}{2}} - ^2S_{\frac{1}{2}}$). Radiated photons are collected by a telescope and registered by a high-speed photon counting detector. Since the lifetime $\tau$ of the excited state is short (\~{}16 ns), the time lag $t$ between pulse transmission and reception gives the range to the emitting atom $z = t/2c$, where $c$ is the mean speed of light on the atmosphere. The number of backscattered photons, detected at a distance $z$ in an interval $dz$ is given by

$$dN_S(z) = \left[ \int \left\{ \frac{P_L(\lambda)\Delta\lambda}{hc} \cdot \eta_{tr} \cdot \sigma_{eff}(\lambda, z) n_{Na} \cdot \frac{A_{tel}}{4\pi z^2} \cdot T^2_{atm}(\lambda) \cdot \eta_{rec} \right\} d\lambda + \frac{q_B}{2c} \right] dz. \quad (8.4)$$
$P_L(\lambda)$ is the fraction of laser power in the wavelength interval from $\lambda$ to $\lambda + \Delta\lambda$ (units nm$^{-1}$), radiated within one laser pulse of length $\Delta t$. $\eta_{tr}$ represents the transmitter efficiency, including all optics transmittances, $\sigma_{eff}(\lambda,z)$ is the effective resonant scattering cross section of one sodium atom at height $z$, $n_{Na}$ is the volume density of sodium atoms, taken within a layer of thickness $\Delta z$. $A_{tel}$ represents the effective collecting area of the telescope and $T_{atm}(\lambda)$ is the transmittance of the atmosphere. The receiver efficiency $\eta_{rec}$ includes all transmittances/reflectivities from all receiver optics, telescope obscuration and detector quantum efficiency. Background counts from dark current and electronics noise are represented by $q_B$, the dark counts per unit time. For our zenith telescope, height $h$ and distance $z$ are equal.

To determine the wavelength dependent laser power with the absorption cross section, the hyperfine structure (see Fig. 8.1) of the $D_2$-line is needed. The interaction of the nuclear spin of the Na atom with the electronic shell splits the $^2P_{3/2}$-level into 4 energy levels and the ground level $^2S_{1/2}$ into 2 energy levels. Thermal motion ($T_{atm} \sim 200$ K at 90 km height) of the sodium atoms broadens the line to a width of approximately 2.5 GHz (She et al. 1992). Atmospheric physicists use narrowband lasers to probe the line shape, thereby extracting information about temperature, wind velocity, etc. For our purpose, we want only to maximize the number of returned photons. If the laser line width is smaller than the Na line width, Na atoms with line-of-sight velocities that put them outside the laser line will not be excited. As there are fewer Na atoms to be potentially excited, saturation will occur more easily. Conversely, if the laser line width is greater than the Na line width, photons with wavelengths outside the Na line will not excite sodium atoms. The best strategy for avoiding saturation and still getting the maximum photon flux, is to match the laser line width to the intrinsic Doppler broadened Na line width. This implies a line width of order 1 or 2 GHz for the laser, taking into account the difficulty of controlling the intrinsic laser wavelength within 1 GHz (corresponding to 1 pm at 589 nm). The laser line width is preset by temporal pulse length and cannot be
Figure 8.1: Hyperfine structure of the Sodium D2-line and resulting line for a temperature of 200 K, comparable to conditions at 90 km height. The laser line, used for the current setup, in red is also shown.

varied in the present setup. The laser has been chosen to match the sodium line width.

With a high-efficiency detector, the predominant noise will be due to photon statistics. Equation (8.4) can be inverted to give the sodium volume density in one bin. Ignoring background counts, the $1\sigma$ uncertainty in the log of this density is

$$\sigma\{\ln[n(z)]\} = \frac{1}{\sqrt{N(z)}}. \tag{8.5}$$

The uncertainty can be reduced by averaging over multiple shots, but at the expense of a corresponding loss in temporal resolution. The CSU data, from which the power spectrum of Equation (8.3) was derived, result from averaging 6000 laser shots taken at a rate of 50 Hz. Our aim is to increase the signal-to-noise ratio without degrading the temporal resolution. This will be achieved by a combination of two factors:

- Increasing $A_{tel}$, the collecting area of the telescope, the detector quantum efficiency
and the throughput of the receiver optics and thereby the number of photons detected.

- Employing averaging in the Fourier domain.

The details of this approach are described in Section 8.4.

8.3 System Design

The lidar system uses a pulsed laser, a launch telescope and beam steering mirror to project a collimated beam vertically through the atmosphere. Backscattered photons are collected by a 6 m liquid mirror telescope, described below, which directs the light to the lidar receiver located at the telescope prime focus. The overall system design is illustrated in Figure 8.2. Some details of the main subsystems are provided below.
Figure 8.2: UBC lidar system design block diagram
8.3.1 The Liquid-Mirror Telescope

The Large Zenith Telescope (LZT) is a fixed, zenith-pointing telescope employing a 6.0 m diameter rotating liquid primary mirror (Hickson et al., 2007). The rotation period of the mirror is 8.5051 s, which gives a focal length of 9.0 m. A film of mercury, with an average thickness of 1.5 mm, forms the reflecting surface. A thin (12.5 $\mu$m) film of Mylar stretched over the mirror protects the mercury surface from wind. Light focused by the primary mirror passes through a four-element refracting corrector that gives seeing-limited image quality over a 22 arcmin diameter field of view. The final focal ratio is 1.67 and the effective focal length is 10.0 m. The corrector is mounted on a focusing stage that compensates for thermal expansion and contraction of the telescope structure. Also attached to this stage is a motorized horizontal translation stage capable of supporting two cameras. A CCD camera used for astronomical observations occupies one camera position. The second position is used for the lidar detector.

8.3.2 Laser Launch Facility

The laser system consists of a Nd:YAG laser pumping a dye laser that is tuned to the sodium D$_2$ resonance line. The pump laser is a Spectra-Physics LAB-170-50 Nd:YAG frequency-doubled laser. It produces 210 mJ pulses at 50 Hz with a wavelength of 532 nm. The laser is cooled by a water-glycol mixture circulating through a refrigerating chiller. (Running water is not available at the remote site of the LZT.) An interlock system protects the laser from any failure of the cooling system.

The 532 nm radiation from the Nd:YAG pump laser is directed to a Cobra-Stretch CSTR-D-24-US dye laser that employs two 90 mm wide 2400 lines per mm gratings. This laser can be tuned from 330-710 nm and we operate it at 589 nm. Pyrromethene 579, dissolved in Ethanol, is used as the dye medium. The resulting line width is 0.04 cm$^{-1}$, which corresponds to 1.2 GHz. The laser is equipped with a main amplifier that boosts
its conversion efficiency to $\sim$50%. The resulting 10 ns pulses have an energy of $\sim$ 100 mJ. The output beam has a divergence of approximately 0.5 mrad. The beam profile can be estimated as a Gaussian with a “burn diameter” (terminology from the laser company Sirah) of approximately $4.5 \times 2.8$ mm. This corresponds to the diameter at which the intensity has fallen to about 2% ($2.8 \sigma$) of the central intensity. The standard deviation of the Gaussian beam along the two principal axes is thus $0.8 \times 0.5$ mm.

The wavelength of the output beam is monitored by a pulsed laser wavelength meter. This instrument uses a Fabry-Perot cavity and a CCD for precise wavelength measurement. The frequency accuracy is $0.02 \text{ cm}^{-1}$ (600 MHz). A feedback loop is used to control the dye laser, maintaining frequency stability.

The main laser beam is expanded to $\sim$12 cm diameter by means of a concave diverging lens and launch telescope. The launch telescope is a refracting telescope with a 15 cm clear aperture and a focal length of 1100 mm, located with the lasers and the laser conditioning optics on the optical bench. The beam divergence can be varied from a diffraction limited parallel beam to several arcmin (the maximum field of view of the lidar detector is 0.7 arcmin) by varying the distance between the diverging lens and the objective lens of the launch telescope. No spatial filter is employed due to the high power of the beam, which would cause an air breakdown at the pinhole location.

The collimated beam produced by the launch telescope is directed to a 25 cm flat mirror mounted on a gimbal stage. This allows the uplink beam to be directed vertically with arcsec precision. The direction of the beam is monitored by a 15 cm Schmidt-Cassegrain telescope equipped with a CCD detector, which images the resulting LGS.
8.3.3 Receiver Optics and Electronics

The lidar detector consists of a chopper wheel, quadrant mirror, reimaging system, and four photomultiplier (PMT) detectors. The chopper wheel, located at the prime focus, protects the PMTs from the bright Rayleigh-scattered light from the uplink beam. The chopper employs a rotating wheel with two cut-outs. The position of the wheel is sensed by a phototransistor, which generates a pulse just before the beam is unblocked. The pulse triggers the laser after an adjustable digital delay. This allows us to set the range of the Rayleigh light that is blocked and ensure that none of the sodium light is lost.

The quadrant mirror is a concave spherical mirror, cut in four quadrants and reassembled with each part tilted slightly off axis. Located in the expanding beam above the prime focus, it splits the light into four equal parts. Each of the resulting four beams then enters a separate optical and detector system. These include lenses that re-image the pupil onto the photocathode, a narrowband filter, and a high-sensitivity PMT. The narrow-band filter is a flat interference filter with 90% central transmission and 260 pm FWHM centered at 588.995 nm. Its purpose is to block background light that is not at the sodium wavelength. In Figure 8.3, a ray trace of the optical system and a photograph of the partly-assembled detector are shown. The other PMT’s are located at 90-degree intervals around the telescope axis on the detector mount.

The PMTs are equipped with GaAsP photo detectors, having a quantum efficiency of 37% at 589 nm. To reduce dark current, the PMT’s are thermoelectrical cooled to a temperature of -5°C. The PMT output is connected to a 1 GHz preamplifier and constant fraction discriminator. Digital pulses, with 4-ns pulse width, produced by the discriminator are transferred from the prime focus to the data acquisition and control computer, located in the LZT control room ~15 m away.

A four-channel multiscaler counting card records the arrival times of the incoming pulses, with respect to a timing pulse produced by the pump laser when it fires. These
**Figure 8.3:** Ray trace of one of four sectors of the receiver system. Light expanding from the LZT prime focus is refocussed by four off-axis spherical mirror quadrants (one is shown), collimating optics, interference filter and focusing lens onto four photomultipliers (one photocathode is shown). The picture shows the partly-assembled detector with one PMT. The support plate for the quadrant mirror, shown upside down, can be seen resting on top of the housing.
are binned in 2 ns intervals, which correspond to a 0.3-meter vertical resolution. The system is controlled by a LabVIEW program running on a PC using a Linux operating system.

8.3.4 Safety Components and Trigger Circuit

The high peak power of the laser requires a system for the protection of aircraft crew and passengers against accidental exposure to the beam. A radar is used to detect approaching aircraft and automatically turn off the laser. For this purpose, we modified a commercial radar in a manner similar to that of Duck et al. (2005). The radar system is connected to the laser interlock system so that any target appearing on the radar immediately shuts down the laser. The system was verified by fly-over tests.

8.4 Expected System Performance

Our laser emits at maximum 100 mJ per pulse (with an average power of 5 W and peak power of 10 MW per pulse). At a mean air-wavelength of 588.995 nm, this corresponds to $3 \times 10^{17}$ photons. The uplink efficiency is 60%, assuming 70% transmission through the atmosphere. This means $1.8 \times 10^{17}$ photons arrive at the sodium layer at each pulse. The convolution of the laser line profile and the Sodium hyperfine lines results in a scattering cross section of $6 \times 10^{-16}$ cm$^2$. The average number of photons per pulse is obtained by multiplying this cross section by the column density. We use a volume density (She et al., 1992) of $4 \times 10^9$ m$^{-3}$, which, when multiplied over an estimated layer thickness of 10 km gives a column density of $4 \times 10^{13}$ m$^{-2}$. The scattering probability is therefore 2.4% and $4.4 \times 10^{15}$ photons are scattered into $4\pi$ sterad (Isotropic spontaneous emission). Our 6 m mirror has a collection probability of $2.8 \times 10^{-10}$ at the average range of 90 km from the scattering process and together with an assumed air transmission of 70%, $8.6 \times 10^5$ photons arrive on the mirror. The receiver’s optical transmittance is 45%,
including obscuration and the transmission of all optics. The PMTs have a photocathode sensitivity of 174 mA W\(^{-1}\), which translates at 589 nm to a quantum efficiency of 37%. The overall receiver efficiency is therefore 16.6% and the number of photons received by the system is 1.4\(\times\)10\(^5\).

The telescope pupil is divided into four quadrants (see Section 8.3.3) with parallel detection lines in order to reduce coincidence losses. The fraction of photons detected is given by

\[
\varepsilon = \frac{1}{1 + \tau_{\text{CFD}} f_i},
\]

where \(f_i\) is the photon arrival rate and \(\tau_{\text{CFD}}\) is the deadtime of the constant-fraction discriminator (CFD). With a mean incoming photon rate \(f_i = 530\) MHz (incident photons arrive over a range of order \(t = 2 \cdot 10^3\) km/c = 66 \(\mu\)s), and \(\tau_{\text{CFD}} \approx 5\) ns, approximately 27% of the incident photons will be detected. Thus a total of \(\sim 4\cdot10^4\) photons are detected from each pulse. With a bin size of 2 m, an average of \(\sim 8\) photons will be detected within each bin.

The mean height of the sodium is given by

\[
\bar{z} = \frac{1}{N} \sum N_i z_i,
\]

where \(N_i\) is the number of photons received the \(i\)-th bin, centered at height \(z_i\) and \(N = \sum_i N_i\). The variance in the mean height is therefore

\[
Var(\bar{z}) = \frac{1}{N^2} \sum \left[ (z_i - \bar{z})^2 N_i \right].
\]

For illustration, suppose that the density of the sodium layer is constant in a uniform layer of thickness \(w\) centered at height \(\bar{z}\) and zero above and below this layer. We divide the layer into \(2m + 1\) equal bins, so \(z_i = \bar{z} + w(i - m)/(2m + 1)\) and the expected number
of photons in each bin is \( N_i = N/(2m+1) \). Inserting this into Equation (8.8) gives

\[
\text{Var}(z) = \frac{2w^2}{N(2m+1)^3} \sum_{i=1}^{m} i^2 = \frac{m(m+1)}{3N(2m+1)^2} w^2.
\]

The 1\( \sigma \) uncertainty in the mean height is therefore

\[
\sigma(z) = \sqrt{\frac{m(m+1)}{3N(2m+1)^2} w} \approx \frac{w}{\sqrt{12N}}.
\]

Taking \( w = 10 \) km and \( N = 4 \cdot 10^4 \), we expect the 1\( \sigma \) uncertainty in the mean height, from a single laser shot, to be approximately 14 m. If we were to average 50 shots, we would obtain 1\( \sigma \) uncertainty of 2 m on a timescale of 1 sec. For comparison, the RMS height fluctuation for frequencies above 1 Hz, obtained by integrating Equation (8.3), is 4 m. Averaging the sodium profiles reduces the time resolution. This is not what we want. Rather, it would be better to average many power spectra taken at the 50 Hz sampling rate in frequency space. The observed mean height \( h_0(t) \), at time \( t \), can be written as

\[
h_0(t) = h(t) + r(t),
\]

where \( h(t) \) is the true mean height and \( r(t) \) is the random error due to the photon noise.

Taking the Fourier transform of this equation and squaring, we obtain

\[
|H_0(v)|^2 = |H(v) + R(v)|^2 = |H(v)+R(v)|^2 + |R(v)|^2 + H(v)R^*(v) + H^*(v)R(v).
\]

The quantity on the left is the power spectrum of the observed data. On the right we have the true power spectrum of sodium mean height fluctuations, to which is added the power spectrum of the photon noise plus two fluctuating quantities whose mean is zero. If we now average many such spectra, taken minutes, hours or days apart, the
fluctuating quantities will average to zero. Thus

\[ \langle |H_0(v)|^2 \rangle = \langle |H(v)|^2 \rangle + \langle |R(v)|^2 \rangle. \quad (8.13) \]

We see that the averaged power spectrum is the sum of the true power spectrum plus the power spectrum of the noise. Since the photon noise has no temporal or spatial correlations, this component will have a flat power spectrum. Its amplitude is known since the number of photons is known. So, by subtracting a flat spectrum of the appropriate amplitude, we can recover the true power spectrum of the mean height with a 50 Hz time resolution.

8.5 Status and Observing Program

At the time of writing this paper, the lidar system has been installed at the LZT and is undergoing calibration and testing. First light is expected in early June 2008. The system will be operated on clear nights over a one-year period to allow the yearly cycle of sodium variability to be studied. Our first-light image of the laser launch is shown in Figure 8.4. We expect that initial results will be released in the third quarter of 2008, and that a full analysis will be completed by the end of the observing program in mid 2009. In general, one night of data suffices to generate a power spectrum of the mean height variability, covering the frequency range of interest to TMT AO systems. As described above, data from many nights can be averaged in frequency space to improve the signal-to-noise ratio, especially on the low frequency side of the spectrum.

The performance of the system is presently limited by our counting card, which has a maximum continuous count rate of only 21 MHz. This limits the number of photons that can be detected to \( \sim 1500 \) photons per shot, about one thirtieth of the expected number that would be received at full laser power. A new card that will allow count
rates of up to 2 GHz is expected to soon be available. Upgrading the system with this card will provide an increase of more than a factor of five in signal-to-noise ratio and will allow the lidar to achieve its full potential.
Figure 8.4: First light of the laser launch facility. On the left hand side, parts of the stabilizing spider of the 6-m mirror, the hexapods of the prime focus, the 25 cm flat and the safety radar as well as the lidar beam are visible. On the lower right, the laser room in action is shown and the LZT enclosure with the uplink beam and a partly opened roof is visible in the upper right. The blue light comes from the laser warning LEDs.
Chapter 9

A Large-Aperture Sodium Fluorescence Lidar with very High Resolution for Mesopause Dynamics and Adaptive Optics Studies

9.1 Introduction

High-resolution observations of the density structure of atomic sodium in the Earth’s mesosphere and lower thermosphere, using a large-aperture lidar system, reveal features of this dynamic region in greater detail. The sodium is highly structured, showing multiple layers that vary in density and altitude on timescales ranging from minutes to hours. Large-scale instabilities and Kelvin-Helmholtz billows are observed along with

\footnote{A version of this chapter has been published slightly modified as Pfrommer, T., Hickson, P., and She, C.-Y., ‘A large-aperture sodium fluorescence lidar with very high resolution for mesopause dynamics and adaptive optics studies’ in the Geophysical Research Letters (GRL). The electronic version of this document offers fully hyperlinked cross-references throughout. We are grateful for support from Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), and the British Columbia Knowledge Development Fund (BCKDF).}
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an overall downward propagation of the layers. Coherent short-period gravity wave oscillations are sometimes seen extending over the entire sodium region. Individual meteor ablation trails produce transient density spikes that last at most a few seconds. The mean sodium altitude is found to have a temporal power spectrum proportional to the $-1.8$ power of the frequency, close to that expected for Kolmogorov turbulence.

It has long been known that the region of atmosphere in the altitude range 75 to 120 km contains a relatively high density of neutral Na, K, Fe, and other metals. These are believed to be produced by the ablation of meteoroids and removed by chemical reactions at the bottom of the region (Plane, 2003). Much has been learned about this region from observations with ground-based lidar systems that employ pulsed lasers tuned to resonance lines of the atoms. By detecting and timing resonantly-scattered photons, one can determine density and, in some cases, temperature and wind velocity as a function of height (Bills et al., 1991, She & Yu, 1994). The relatively small size of typical lidar telescopes has limited the achieved spatial and temporal resolution to a few hundred meters and a few minutes (She & Yu, 1994). Such observations have revealed variability in the sodium density vertical structure, with perturbations on a scale of several kilometers to tens of kilometers that are thought to be produced by mesospheric gravity waves. These waves were first seen in noctilucent cloud observations and were subsequently characterized from airglow images (Peterson & Kieffaber, 1973, Taylor et al., 1987), before their routine observations by modern lidars (Liu et al., 2004a, Li et al., 2009).

Statistically, the sodium density is centered between 88 and 92 km with a full-width at half maximum of about 10 km (Plane, 2003). Occasionally, high-density sporadic sodium layers (SSls) are reported. These are described as thin layers (1 to 4 km thick) of enhanced density (at least twice that of the background) superimposed on the background sodium distribution and lasting for at least tens of minutes (Nagasawa & Abo, 1995, Dou et al., 2009). Despite much study of SSLs in the past two decades, their cause is still
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an open question. However, the ion recombination mechanism invoking windshear and sporadic E-layer, appears to be consistent with many observed characteristics (Clemesha et al., 1999, Collins et al., 2002, Williams et al., 2007).

9.2 Observations

The Large Zenith Telescope (LZT) lidar system (49.3°N, 122.6°W) employs a Nd:YAG-pumped dye laser producing 10 ns pulses at 50 Hz with a mean power of 5 W, centered at 589.1 nm (Pfrommer et al., 2008). Backscattered photons are collected with the 6-meter mercury primary mirror of the LZT. The detector, located at the telescope’s prime focus, employs four high-efficiency photomultipliers (40%) and a fast counting system (2 ns pulse resolution and 32 ns/4.8 m bin width) that detect over 1500 backscattered photons per laser shot. This allows the sodium region to be studied with meter-scale spatial resolution and sub-second temporal resolution. (Similar photon returns are achieved by the University of Illinois Na lidar system, using US Air Force tracking telescopes of 3.5 and 3.7 m diameters. However, the temporal and spatial resolution of published temperature, wind and Na density measurements from that system is 90 s and 0.5 km (Liu et al., 2004a, Gardner & Liu, 2007). This compares with our Na density resolutions of (1 s/24 m), (60 ms/15 m) and (40 ms/9.6 m), respectively in Figures 9.1, 9.2 and 9.3.

The LZT lidar system began operation in July 2008 and collected more than 80 hours of data in summer 2008. Examples of sodium density profiles are shown in Figure 9.1. It is evident that the mesospheric sodium region is complex and dynamic. Individual sodium layers appear rapidly, sometimes over a period of a few minutes, and usually persist for several hours. They drift in altitude and often show strong wave-like undulations. Because the lidar probes the density along a vertical line, variations will occur as the sodium clouds are carried across the laser beam by the mesospheric wind. Thus, the changes that we see are some combination of intrinsic temporal changes, and spatial
Figure 9.1: Sodium density maps, on four nights, obtained with the LZT lidar system. The density of sodium atoms, proportional to the brightness scale, is shown as a function of altitude and time. Multiple transitory layers can be seen, which evolve in density, altitude and structure. The density in the brighter layers is typically two to three times that of the background. The black vertical bars correspond to times when the laser was shut down due to overlying aircraft.
Figure 9.2: Onset of turbulence in the mesospheric flow. Vortices can be seen developing at the bottom of this stratified layer, and then breaking to form a turbulent wake. The scale of the first vortex is ∼1 km. Assuming that it is circular, the inferred wind speed is 16 ms$^{-1}$.

variations along the direction of advection. It is plausible that many of the temporal changes, at least on short timescales, could be dominated by advection rather than intrinsic evolution of the clouds themselves. The sodium region typically consists of thin layers, as clearly seen in the 2nd and 3rd panels of Fig. 9.1.

What is the cause of these discrete components? Formation by ablation of single meteoroids can be ruled out because the bulk of the metals deposited by meteoroids comes from objects with mass in the range 10$^{-10}$ to 10$^{-7}$ kg (Love & Brownlee, 1993). This is too small a mass to account for the observed discrete layers if they have horizontal dimensions consistent with their observed durations and typical mesospheric wind velocities. A more likely explanation is that advection by mesospheric gravity waves has created regions of higher sodium density. These waves, as described in a recent comprehensive review (Fritts & Alexander, 2003), are thought to originate in the troposphere. As they propagate upwards into the much lower density regions of the upper atmosphere, energy
conservation demands that their amplitudes grow exponentially. In the mesosphere these waves can reach displacements as large as several km and velocities of tens of \( \text{ms}^{-1} \). The layers that we see may correspond to the crests of such waves. Gravity waves have an unusual property in that the vertical component of the group velocity and phase velocity has opposite signs, and for upward propagating waves, the phase fronts of the layers move downwards with time. Sometimes, denser sodium clouds appear, such as the bright feature seen in the third panel of Fig. 9.1 between 7 and 11 UTC, which have peak sodium densities that are several times that of the background. These satisfy the criteria for SSLs; for example, the dense layer at \( \sim 9 \) UTC has a peak intensity 3.5 times greater than the background at 94 km and a FWHM of \( \sim 2 \) km. If the ion-recombination origin of Na layers is correct, the downward propagation of wave phase fronts would thus lead to a downward progression of sodium layers. This is consistent with our observations, as shown in Fig. 9.1. Extensive coherent oscillations in the sodium density can be seen in the third panel of Fig. 9.1 around 7 UTC, extending over more than 15 km in altitude. They show an apparent period of \( \sim 4 \) min, which suggests that we are seeing gravity waves directly throughout the sodium layer. However, as we are unable to measure the background wind velocity, we cannot determine the intrinsic frequency of the waves (Fritts & Alexander, 2003). Another interesting feature is overturning in the sodium density, characterized by two maxima in the vertical density profile at a given time, as can be seen between 10 and 11 UTC in the second and third panels of Fig. 9.1 between 90 and 95 km. Such overturning, observed previously by other metal lidars, may indicate convective instability, which, though not firmly established, is a topic of current interest (Hecht et al., 2004; Xu et al., 2006). We find clear evidence for dynamic instability by direct observation of Kelvin-Helmholtz (K-H) billows in the mesospheric flow. In the top panel of Fig. 9.1 plumes can be seen extending down from the bottom of the sodium layer. Fig. 9.2 shows a high-resolution (60 ms and 15 m) density map recorded on July 11, 2008.
Here we see a system of vortices developing at the bottom of a sodium cloud. The vortex height is on the order of 1 km. Although the presence of K-H billows has long been implicated by the observation of short-period ripples in all sky images (Hecht et al., 2005), we know of no previous direct observations of mesospheric K-H billows. In addition to these dynamical features, localized events are seen in which the sodium density increases by an order of magnitude for a few seconds or less over a region that extends less than 100 m in altitude. An example is shown in Fig. 9.3. Similar events have been seen at lower resolution in Na, Fe, Ca and K and are caused by meteor trails drifting across the laser beam (Kane & Gardner 1993, von Zahn et al. 1999). We typically detect several of these per night, mostly below 87 km altitude. This might be an indication of the size and mass of the incoming meteors, responsible for the transient peaks. Unless

![Figure 9.3: Meteor vapor trails. This event, detected on July 16, 2008, exhibits two peaks, possibly due to a meteoroid that split in two. The vertical width of each component at half maximum is ~50 m and ~30 m and the duration is ~0.6 s. The peak sodium density in each event is more than 20 times the average density of sodium at this altitude (the color scale indicates photon counts per 40 ms × 9.6 m bin).](image-url)
for the smooth background, which is caused by meteonic dust in the microgram range (see Fig. 4.8) that ablate in the ionosphere and recombine at the top of the layer, these transients are larger and atmospheric braking therefore ablation is caused in denser areas, resulting in a plume of sodium near the bottom of the layer.

Another quantity of interest is the power spectrum of sodium density, which has implications for wave and turbulence dynamics. Direct measurements of the density power spectrum are hampered by fluctuations in laser power and atmospheric transparency. However, the mean sodium altitude (the density-weighted first moment of altitude) is unaffected by such instrumental and atmospheric noise. The temporal power spectral density of this quantity, derived from one night of data, is shown in Fig. 9.4.

![Figure 9.4: Power spectral density of the sodium mean altitude, derived from data obtained on the night of August 6, 2008. The straight line corresponds to a power law index of -1.9. The peaks at multiples of 5.5 Hz are due to noise in the receiver system.](Image)

The straight line shows the power law relationship, which provides a reasonable fit over four decades of frequency. This temporal power spectrum is directly related to the
spatial power spectrum of Na density fluctuations, which can be seen as follows: At any given height, advection of turbulent structure across the laser beam maps spatial frequencies to temporal frequencies. The shape of the power spectrum is unchanged, and the amplitude is scaled by a function of the wind velocity. For Kolmogorov turbulence the one-dimensional spectrum is a power law with an index of $-5/3$, which results in a temporal power spectrum with the same slope. Since the mean altitude is a linear function of uncorrelated density fluctuations at different altitudes, a Kolmogorov density spectrum will give rise to a mean-altitude spectrum having a power-law index of $-5/3$. The observed index is close to this, but slightly steeper; this may signify a departure from (inertial range) turbulence dominance, implicating contributions from short-period gravity waves. Indeed, the observed power spectral densities of wind and temperature have indices varying between $-1.5$ and $-2.5$ over the range $10^{-4}$-$10^{-2}$ Hz [Liu 2007], consistent with our observed index of $-1.8$ over a frequency range that is two decades greater. Significant power may extend to frequencies as high as $\sim 100$ Hz, corresponding to a length scale of $\sim 0.1$ m, the mean free path at this altitude. However, a downturn is expected at a scale of $\sim 10$ m, given turbulent energy dissipation rates measured by rockets [Lübken 1997].

9.3 Discussion

The profiles shown in Figs. 9.1 and 9.2 have more than 100 times the temporal resolution and about 10 times the vertical resolution of previous studies, revealing features and details not previously seen. Clearly, the dynamics of this region are complex, involving waves, wind, instability and turbulence. We confirm the presence of overturns, Kelvin-Helmholtz rolls and coherent short-period gravity waves in the mesosphere. The details of the fine-scale flow and their impacts on the dynamics of the region are interesting research topics, and may help to constrain global circulation models (GCMs, current gravity wave
parameterization schemes employed in GCMs are presently unable to produce realistic outputs for the mesosphere (Yuan et al., 2008). These and future high-resolution observations, combined with theoretical analysis and modeling, will ultimately lead to a better understanding of this interesting region of the atmosphere. The structure and dynamics of the sodium region are also important for astronomy. Large ground-based telescopes employ laser adaptive optics systems to mitigate the blurring effects of atmospheric turbulence. In these systems, continuous-wave lasers excite mesospheric sodium atoms, producing artificial laser guide stars, which are used to measure the optical phase distortion produced by index of refraction fluctuations. The phase distortion is then corrected by deformable mirrors. In this way near-diffraction-limited resolution and high sensitivity are achieved. However, the vertical extent of the sodium layer, and its varying internal structure, creates errors that increase with telescope aperture (Herriot et al., 2006). The performance of the system depends on the sodium mean-altitude power spectrum at high frequencies. The LZT lidar data extend previous work to the critical high-frequency region and will provide essential input to the design of next-generation large optical telescopes (Davis et al., 2006, Thomas et al., 2008).
Chapter 10

High-Resolution Lidar Observations of Mesospheric Sodium and Implications for Adaptive Optics\textsuperscript{1}

10.1 Introduction

The Earth’s mesosphere and lower thermosphere contains a region of atomic metals deposited by meteoric ablation \cite{Plane2003}. Laser adaptive optics systems commonly create artificial laser guide stars (LGS) in this layer by resonant excitation of sodium atoms \cite{Beckers1993}. The sodium region has a typical vertical extent with an effective full width at half maximum of order 12 km and a mean altitude of roughly 91 km. LGS so-produced are cylindrical in shape and appear star-like only when viewed exactly end-on. The finite thickness of the region becomes an important factor for very large

\textsuperscript{1}A version of this chapter is published as Pfommer, T. and Hickson, P., ‘High-resolution lidar observations of mesospheric sodium and implications for adaptive optics’ to the Journal of the Optical Society of America A (JOSA A). The electronic version of this document offers fully hyperlinked cross-references throughout. We are grateful for support from Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation (CFI), and the British Columbia Knowledge Development Fund (BCKDF).
The sodium lidar system of the University of British Columbia employs a pulsed frequency-doubled Nd:YAG laser pumping a dye laser tuned to the sodium D$_2$ resonance transition at a wavelength of 589.0 nm in air (Pfrommer et al., 2008). The pulse repetition rate is 50 Hz and the pulse length is 7 ns. The typical transmitted pulse energy is 100 mJ, giving a mean output power of 5 W. The beam is collimated, with a half-power width of
10 cm, and projected vertically. Returned photons from the sodium region are collected by the Large Zenith Telescope - a zenith-pointing astronomical telescope employing a 6-meter f/1.5 parabolic rotating liquid primary mirror (Hickson et al. 2007). The lidar detector, located at the telescope’s prime focus, employs a segmented collimator to divide the beam to feed four identical detectors in order to reduce counter coincidence losses. Each channel includes pupil imaging optics, a narrow-band sodium-wavelength filter with a band width of 0.3 nm, and a high-speed high-efficiency photomultiplier. The power-aperture product of the system is 150 Wm\(^2\), enabling it to provide raw vertical profiles of sodium density with a spatial sampling of 3.6 m and a temporal sampling of 20 ms.

### 10.2 The Sodium Density Structure

An example of a sodium density map, from one night of observations, is shown in Fig. 10.1. The ordinate represents the altitude in km above sea level and the abscissae is time. The brightness of the image is proportional to sodium return flux. The raw counts have been re-binned to 75 m and 1.3 sec to improve the signal-to-noise ratio. In order to better match the response of a typical sodium LGS AO system, the received counts are not corrected for the geometrical change in solid angle with height. The data cannot be linked to absolute sodium density as no instantaneous Rayleigh scattering from lower altitudes was recorded due to limitations of the counting system. A recent upgrade has overcome this limitation so it should be possible to calibrate future data using the methods described in Tilgner & Zahn (1988), Fricke & von Zahn (1985), Gardner et al. (1986).

Fig. 10.1 and similar maps from more than 30 nights of data, show a variety of structure. The mesopause region has strong wind shear, with horizontal wind velocities varying from as much as 60 ms\(^{-1}\) to near zero over a vertical distance of 20 km (Yuan...
Figure 10.1: Sodium density evolution with the sodium layer advecting across the collimated vertical laser beam. The intensity in the color scheme is photon counts per (1.3 sec / 75 m)-bin and is given as a function of altitude and time. The four gaps in the data result from automatic system shutdowns caused by over-flying aircraft. The received flux has been fit with a 5th order polynomial in time and each single sodium profile is scaled to remove the residuals. This corrects short-term variations in laser power (due primarily to temperature cycling in the laser cooling system) while long-term changes, which can be attributed to sodium density variations, are preserved. The centroid altitude is identified by a white line, superimposed on the map.
Dynamic instabilities, turbulence, and Kelvin-Helmholtz vortices can be seen developing in the stratified flow (Pfrommer et al., 2009). Multiple sodium layers are evident. These evolve with time and often dominate the structure. At other times relatively-weak layers are superimposed on a comparatively-smooth sodium background. The lifetime of an individual layer is typically several hours. Some layers appear rapidly and can reach densities that are an order of magnitude greater than the mean sodium background. These sporadic sodium layers (SSLs) can cause shifts in the mean sodium altitude of several km in just a few minutes.

Wave-like undulations in the sodium density, with periods of several minutes, are apparent in Fig. 10.1. Coherent oscillations can be seen extending vertically throughout the entire sodium region, sometimes phase shifted with increasing altitude. These result from gravity waves that are generated in the troposphere. As they propagate upward, energy conservation demands that they grow in amplitude. At the altitude of the sodium layer, where the atmospheric density is six orders of magnitude lower than it is at sea level, gravity waves reach amplitudes of order one km or more and velocities of tens of $\text{ms}^{-1}$. As the waves become nonlinear they dissipate, injecting energy into the region. Vertical displacement of air results in density variations. Because of the strong vertical gradients of sodium abundance in this region, enhancements in sodium density can be several times that of atmospheric density fluctuations (Gardner & Shelton, 1985), giving rise to the observed layers. Most show evidence of a general downward drift with time. This is consistent with a gravity wave origin as these waves have a downward vertical phase velocity component, even though the group velocity is directed upwards (Fritts & Alexander, 2003).

The upper limit of the sodium layer is defined by the recombination of ablated sodium ions and free electrons from the ionosphere and by the cross section for meteor ablation. The former is affected by variations in electron density (space weather) and the latter by variations in the meteor influx rate. Significant variations in the density and extent
of the upper sodium region are seen, sometimes on a timescale of minutes. The lower boundary is more sharply defined. It marks the altitude at which the rate of removal of sodium atoms by chemical reactions matches the meteoric sodium deposition rate.

Most of the meteoric mass ablated in the upper atmosphere comes from Earth-crossing interplanetary particles in the mass range from 0.1 to 100 µg (Ceplecha et al., 1998). These meteors are not uniformly distributed across the Earth’s orbit, but show clumpiness originating from the orbit and mass distribution of their parent comets, whether recent (producing meteor showers) or long decayed (Brown et al., 2010). In addition, dust particles from the asteroid belt can eventually reach the Earth’s orbit (Plane, 2003). The meteoroid influx results in an absolute number density of sodium atoms in the upper atmosphere that is about a factor of $10^8$ smaller than that of air molecules. The structure maps show therefore upper atmospheric dynamics as traced by the sodium atoms. Sodium is a volatile element that ablates at lower temperatures than more abundant refractory elements. This, combined with the large absorption cross section of the resonance D$_2$-line, makes sodium attractive for adaptive optics. The photon return is substantially larger for Na than for Ca or Fe, whose products of column abundances and respective resonance cross sections are depleted, compared to sodium, by as much as two orders of magnitude (Plane, 2003).

We frequently see events, lasting from sub-second timescales to several tens of seconds and extending a maximum of a few hundred meters in height. These events have been identified as ablated metals from incoming meteors whose plumes are carried across the laser beam by the prevailing wind (Kane & Gardner, 1993). When such events occur far from the mean sodium altitude and are sufficiently strong, they significantly change the mean altitude, sometimes by as much as 1 km over time periods on the order of 1 s. These are discussed further in Section 10.5. Apart from the well-studied SSLs (see Clemesha, 1995 and references therein), these transient effects appear on much shorter time-scales and have therefore potentially a stronger effect on the response of an AO
control system, which is able to compensate for slow variations in the sodium density profile. SSLs appear on time scales of minutes and the mean altitude will change on such time scales. However centroid algorithms in AO systems should be able to follow such changes if sufficiently bright NGS are in the field of view.

The variety and variability of structure in the sodium region suggest a statistical approach, discussed in the next sections.

10.3 The Fluctuation Power Spectrum

The altitude of the centroid of the vertical sodium density profile, hereafter called the centroid altitude, is defined by

\[
a(x,y,t) = \frac{1}{N(x,y,t)} \int_{0}^{\infty} n(x,y,z,t)zdz,
\]

(10.1)

where \( n(x,y,z,t) \) is the number density of sodium atoms as a function of position \((x,y)\) in the horizontal plane, altitude \(z\) and time \(t\), and

\[
N(x,y,t) = \int_{0}^{\infty} n(x,y,z,t)dz.
\]

(10.2)

is the sodium column density. The centroid altitude is a robust parameter that is readily measured by a lidar and does not require knowledge of the absolute sensitivity or efficiency of the system. Variations of the centroid altitude translate directly to focus errors for any sodium AO system employing cw lasers. For a telescope of diameter \(D\) at altitude \(h\) observing at zenith angle \(\zeta\), the piston-removed rms wavefront error (averaged over the telescope aperture) resulting from an altitude variation \(\Delta a\) is

\[
\sigma_{wfe} = \frac{D^2 \sin \zeta}{16 \sqrt{3} (a-h)^2} \Delta a.
\]

(10.3)
For a thirty-meter telescope observing near the zenith, this corresponds to a wavefront error of approximately 4 nm per meter of altitude variation. A typical one-sided centroid altitude temporal power spectral density (PSD) is shown in Fig. 10.2. The raw spectrum is well fit by the model

\[ P_a(\nu) = \alpha \nu^\beta + \gamma, \]  

Figure 10.2: Temporal one-sided power spectral density of centroid altitude. The spectrum is fit well by a power law of index $-1.97$ and amplitude of 31 m$^2$Hz$^{-1}$ plus a constant photon noise floor. The figure shows the noise-subtracted spectrum, filtered with a logarithmic boxcar having a reciprocal width $\nu/\Delta \nu=128$. The noise floor is indicated by a horizontal dashed line. The vertical dashed-line indicates the Brunt-Väisälä frequency. No systematic deviations from a power-law are evident over the 4-5 orders of magnitude range of the spectrum. The small resonance seen at 5.5 and 11 Hz are believed to arise from instrumental effects and the apparent flattening above a few Hz is an artifact caused by negative values not appearing on the plot. Superimposed in a light grey dashed line is a low-frequency spectrum, extending up to $10^{-2.4}$ Hz, derived using data from the Colorado State University lidar (Davis et al., 2006).
Chapter 10. Sodium Layer Observations and Adaptive Optics Implications

where $\nu$ is the fluctuation frequency. Since the power spectrum of a stochastic process is exponentially distributed (Vaughan (2010) and references therein), the probability of obtaining a measured spectral value $D(\nu)$ given the model $P_a(\nu)$ is given by

$$p[D(\nu)|P_a(\nu)] = \frac{1}{P_a(\nu)} \exp\left(-\frac{D(\nu)}{P_a(\nu)}\right).$$

(10.5)

Therefore, our approach is to maximize the log likelihood $-\sum [D(\nu)/P_a(\nu) + \log P_a(\nu)]$ where the summation is taken over all frequency values in the spectrum. The maximization is done by means of a Markov Chain Monte Carlo (MCMC) method, which also provides a direct estimate of the uncertainties of the fitting parameters. The noise floor $\gamma$, is treated as a free parameter. In practice, values found from the fit agree well with the calculated photon noise variance, indicating that our data are photon-noise limited.

The spectral index $\beta$ ranges from $-1.8$ to $-2.1$ for different nights, with a typical value of $-1.95 \pm 0.12$. The error indicates the standard deviation from results of 14 nights in July and August 2008. The fitting confidence level for each separate night is typically 1.5%. We find a typical value of $\alpha \simeq 30 \pm 20$ m$^2$Hz$^{-1}$ for the amplitude $\alpha$. While the power-law fit (photon noise subtracted) is remarkably good, the wide range of normalization values and in PSD slopes reflect the highly dynamic nature of the sodium layer.

Rocket measurements (Chandra et al., 2008) indicate that the inner scale of turbulence in the mesosphere is of order 10 m. With a typical average wind speed of $\sim 23$ ms$^{-1}$ (Yuan et al., 2008), we would thus expect the PSD to turn down above a few Hz. In any case, the power law is not expected to continue much above $\sim 30$ Hz. This frequency corresponds to the advection of spatial scales of $\sim 1$ m, the mean free path at the sodium altitude. Molecular viscosity will attenuate fluctuations on smaller scales.

Another quantity of interest is the centroid velocity $v_a(t) = \dot{a}(t)$. By the Fourier derivative theorem, its Fourier transform $\tilde{v}_a(\nu)$ is $2\pi i \nu \tilde{a}(\nu)$, hence the centroid velocity
can be derived from the centroid altitude PSD. From the centroid velocity power spectrum
one can calculate the mean-square centroid velocity over any temporal bandwidth by
multiplying the appropriate filter function and integrating over frequency. For example,
the mean square centroid velocity averaged over time $T$ (in units of [sec]) is given by

$$
\sigma_v^2(T) = \frac{1}{\pi^2T^2} \int_0^\infty P_v(v)[\sin(\pi v T)]^2 v^{-2} dv
$$

$$
= \begin{cases} 
2(2\pi)^{-\beta-1} \alpha \Gamma(\beta+1) \sin(\pi \beta/2) T^{-\beta-3}, & \text{if } -3 < \beta < -1, \\
2\pi^2 \alpha T^{-1}, & \text{if } \beta = -2 
\end{cases}
$$

(10.7)

This approach is more robust than estimation of centroid velocities by differentiation of
noisy centroid altitude time series. With typical values of $\alpha$ and $\beta$ and a time interval of
1 sec, the rms centroid velocity is $\sim 24$ ms$^{-1}$. Table 10.1 lists rms centroid velocities for
bandwidths of 1 sec and 10 sec for $\alpha$ and $\beta$ values spanning a $\pm 1$-standard deviation
range.

10.4 Spatial Variations

The high horizontal wind velocity in the mesosphere suggests that much of the observed
high-frequency temporal variation may arise from the advection of spatial structure
(certainly this is true for the meteor trails). Thus, we anticipate that significant spatial
variations in the sodium density structure exist, and that this will result in spatial
variations in the centroid altitude. Such variations may be important for AO systems
that employ multiple LGS directed at different angles on the sky.

It is generally accepted that the near-horizontal density enhancements seen in the
Table 10.1: Root mean square centroid velocities (ms\(^{-1}\)) for 1 s and 10 s bandwidth and a representative range of power spectrum parameters

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Spectral index</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>m(^2)Hz(^{-1})</td>
<td>1 sec</td>
<td>10 sec</td>
</tr>
<tr>
<td>-1.85</td>
<td>12.8</td>
<td>3.4</td>
</tr>
<tr>
<td>10</td>
<td>-1.95</td>
<td>13.6</td>
</tr>
<tr>
<td>-2.05</td>
<td>14.6</td>
<td>4.9</td>
</tr>
<tr>
<td>-1.85</td>
<td>22.1</td>
<td>5.9</td>
</tr>
<tr>
<td>30</td>
<td>-1.95</td>
<td>23.5</td>
</tr>
<tr>
<td>-2.05</td>
<td>25.2</td>
<td>8.5</td>
</tr>
<tr>
<td>-1.85</td>
<td>28.5</td>
<td>7.6</td>
</tr>
<tr>
<td>50</td>
<td>-1.95</td>
<td>30.4</td>
</tr>
<tr>
<td>-2.05</td>
<td>32.6</td>
<td>10.9</td>
</tr>
</tbody>
</table>

sodium region arise primarily from vertical transport by gravity waves (Gardner & Shelton, 1985). Under the action of a gravity wave, the air molecules undergo oscillations in displacement and density. The sodium atoms act as a tracer of the overall atmospheric motion (Hickey & Plane, 1995). Such oscillations are evident in Fig. 1.

For a steady, linear wave, the vertical displacement \(z'\) has the form (Fritts & Alexander, 2003)

\[
 z'(x,y,z,t) = A \exp[z/2H + i(o t - kx - ly - mz)], \tag{10.8}
\]

where \(k, l\) and \(m\) are components of the wave vector, \(o = 2\pi v\), \(A\) is the complex wave amplitude and \(H\) is the atmospheric scale height. A primed symbol denotes the deviation from the mean value. The resulting variation of the centroid altitude is found by weighting
the vertical displacement by the mean sodium density distribution \( n_0(z) \) and integrating over altitude,

\[
a'(x,y,t) = A \exp[a/2H + i(\omega t - kx - ly)] \frac{1}{N} \int_0^\infty n_0(z) \exp[(z-a)/2H - imz] dz. \tag{10.9}
\]

Setting \( x = y = 0 \) in Eqn. (10.9), we see that the contribution of the waves to the temporal PSD of centroid altitude is

\[
P_a(k,l,m,\omega) = G(m) P_z(k,l,m,\omega) \tag{10.10}
\]

where \( P_z = |A|^2 \exp(a/H) \) is the joint temporal and spatial PSD of gravity wave vertical displacement, at the sodium centroid altitude, and

\[
G(m) = \left| \frac{1}{N} \int_0^\infty n_0(z) \exp[(z-a)/2H - imz] dz \right|^2 \tag{10.11}
\]

is a filter function that embodies the partial cancellation that occurs at short vertical wavelengths due to opposite displacements occurring at different altitudes within the sodium region. For a Gaussian distribution of sodium density, with centroid \( a \) and standard deviation \( \sigma_s \), the integral can be done analytically with the result

\[
G(m) = \exp(\sigma^2_s/4H^2 - \sigma^2_s m^2). \tag{10.12}
\]

This shows that the spectrum of sodium centroid altitude variations arising from gravity waves is cut off exponentially for waves having vertical wave numbers greater than \( |m| \sim \sigma_s^{-1} \).

For an ensemble of gravity waves having a range of amplitudes, wave numbers and frequencies, the total contribution to the centroid altitude PSD is found by integrating
over all wave vectors

\[ P_a(\omega) = \int_{-\infty}^{\infty} G(m)P_z(k,l,m,\omega)dkdlm. \] (10.13)

Similarly, setting \( t = y = 0 \) in Eqn. (10.9) gives the spatial centroid altitude PSD in the horizontal \( x \) direction,

\[ P_a(k) = \int_{0}^{\infty} d\omega \int_{-\infty}^{\infty} G(m)P_z(k,l,m,\omega)dldm. \] (10.14)

Observations indicate that the temporal PSD of atmospheric density fluctuations is a power law with spectral index close to \(-2\) \cite{Senft1993}. Since density fluctuations are proportional to displacement, the density PSD is proportional to the vertical displacement PSD. Eqn. (10.13) thus predicts that the sodium centroid altitude spectrum \( P_a(\omega) \propto \omega^{-2} \), in good agreement with our observations.

Both theory \cite{Gardner1998} and observations \cite{Fritts1989} indicate that the horizontal wavenumber PSD of atmospheric density fluctuations has a power-law index of \( \sim -2 \). Eqn. (10.14) indicates that the horizontal PSD of centroid altitude variations should have the same spectral index.

Despite the good agreement of the gravity wave results with our observed temporal spectral index, it is not obvious that this analysis can be extended to the frequencies of importance for AO. The dispersion relation for high-frequency gravity waves (for which Coriolis effects can be neglected) is \cite{Fritts2003},

\[ \omega^2 = \frac{\omega_0^2(k^2+l^2)}{k^2+l^2+m^2}, \] (10.15)

where \( \omega_0 \) is the Brunt-Väisälä (buoyancy) frequency. From this we see that the maximum possible wave frequency is \( \omega_0 \), which in the mesosphere has a value of \( \sim 0.003 \) Hz \cite{Bills1993}, far below the frequencies of importance for AO. The dispersion relation
relates spatial and temporal frequencies in the rest frame of the fluid. In the presence of
bulk flow (wind), the wave frequencies can be Doppler boosted above the Brunt-Väisälä
frequency \cite{Fritts1987}. However, to achieve frequencies even as high as 1
Hz, with a typical wind speed of 30 ms\(^{-1}\) requires a horizontal wavelength of \(\sim 30\) m.
This is much shorter than the several hundred km that is typical for atmospheric gravity
waves \cite{Fritts1989}.

Effectively, such high frequency fluctuations must arise from the advection of small-
scale density structure by the wind. Whether the structure being advected was produced
by coherent gravity wave oscillations, instabilities, or turbulence is of secondary impor-
tance. We note that advection of pure Kolmogorov turbulence results in a temporal
centroid altitude PSD that has an index of \(-5/3\) (Appendix A), slightly flatter that
what we observe. It is possible that at high frequencies the spectrum results from some
combination of gravity-wave and turbulent structure, although one expects that turbulent
dissipation should dominate on small scales.

At frequencies where the temporal spectrum is dominated by advection, temporal
fluctuations can be related to spatial fluctuations in the direction of the wind (Appendix
A). The structure function of sodium centroid altitude, \(D_a(x) = \langle [a(0) - a(x)]^2 \rangle\), describes
the mean-square altitude difference between two LGS as a function of the component \(x\)
of their horizontal separation at the sodium altitude that is parallel to the direction of
the mesospheric wind. From Eqns. \eqref{eq:10.31} and \eqref{eq:10.36} of Appendix \ref{sec:appendix10.7}, it has the form

\[
D_a(x) = \begin{cases}
2(2\pi)^{-\beta-1} \Gamma(\beta + 1) \sin(\pi\beta/2)\tilde{v}^{\beta+1} \alpha x^{-\beta-1}, & -3 < \beta < -1, \\
2\pi^2 \tilde{v}^{-1} \alpha |x|, & \beta = -2
\end{cases}
\]  \hspace{1cm} (10.16)

where \(\tilde{v}\) is a weighted mean wind speed. Taking \(\tilde{v} = 23\) ms\(^{-1}\), which is typical for the time
of year that our data were obtained, we obtain with the PSD parameters from Fig. \ref{fig:10.2}
\(D_a(r) \approx 28 r^{1.0} \text{ m}^2\). From this we see that the rms difference of the mean sodium altitude
is approximately 27 m for a horizontal separation of 26.5 m (1 arcmin as seen by the telescope), and grows roughly as the square root of the separation. This is consistent with the result from Section 10.3 where the rms centroid velocity for a 1 sec bandwidth was estimated from the temporal PSD to be 24 ms$^{-1}$. Combining this result of the temporal structure function with Eqn. (10.3), we see that focus errors between LGS with a 1 arcmin separation will be of order 100 nm for a 30 m telescope, and of order 200 nm for a 42 m telescope. If such errors are important for multi conjugate adaptive optics is subject to further studies in the design process for ELTs. The potential impact of this on AO systems is considered in Section 10.6. Table 10.2 shows rms centroid altitude variation and wavefront error for a range of PSD parameters and wind speeds.

### Table 10.2: Root mean square sodium centroid altitude variation for a 1 arcmin LGS separation, for a representative range of power spectrum parameters and wind velocities. The rms wavefront error for a 30-m aperture diameter is shown in parenthesis

<table>
<thead>
<tr>
<th>Amplitude m$^2$Hz$^{-1}$</th>
<th>Spectral index</th>
<th>Mean horizontal wind velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7ms$^{-1}$</td>
<td>15ms$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>1.95</td>
<td>27.7 (109)</td>
</tr>
<tr>
<td></td>
<td>2.05</td>
<td>27.0 (106)</td>
</tr>
<tr>
<td></td>
<td>1.85</td>
<td>49.8 (195)</td>
</tr>
<tr>
<td>30</td>
<td>1.95</td>
<td>48.0 (188)</td>
</tr>
<tr>
<td></td>
<td>2.05</td>
<td>46.8 (184)</td>
</tr>
<tr>
<td></td>
<td>1.85</td>
<td>64.3 (252)</td>
</tr>
<tr>
<td>50</td>
<td>1.95</td>
<td>62.0 (243)</td>
</tr>
<tr>
<td></td>
<td>2.05</td>
<td>60.4 (237)</td>
</tr>
</tbody>
</table>
10.5 Meteor Trails

Examples of transient spikes in the sodium density, due to meteor ablation trails, are shown in Fig. 10.3. Most are found near the bottom of the sodium region, between 80 and 85 km. These trails are highly localized, typically a few tens of meters across, and last from a fraction of a second to several tens of seconds. The densities in the trails can be more than an order of magnitude higher than that of the background.

We typically detect up to \(~\sim\) 20 meteor trails per hour. Most are small and have no serious impact on the centroid altitude (less than a two standard deviation change in the altitude, using a 0.4 sec running mean). However, typically one or two meteors per hour do change the centroid altitude significantly. Fig. 10.4 shows a meteor trail event in more detail, indicating its effect on the centroid altitude.

![Figure 10.3: Meteor trails. Spikes in the sodium density occur when meteor ablation trails drift across the laser beam. The figure shows sodium density (vertical scale) as a function of altitude (right scale) and time (left scale) for a typical night.](image-url)
Figure 10.4: A strong meteor trail occurring ∼6 km below the sodium centroid altitude. The intensity map represents number of photons per 10 m/60 ms bin. Its effect on the centroid altitude can be seen in the lower plot. Superimposed on the centroid altitude plot is a low-pass filtered time series (dashed line). Meteor ablation temporarily changes the centroid altitude by 0.6 km (beginning of event) to 0.8 km (end of event) in approximately one second.
10.6 Implications for Adaptive Optics

Focus errors arising from sodium centroid altitude variations couple into AO performance in several ways. Since sodium altitude fluctuations cannot be distinguished from atmospheric focus changes (for cw laser systems), focus information on long time-scales must come from natural guide stars (NGS). However, most NGS are not sufficiently bright to provide reliable focus information on short time scales, so this information must come from the LGS. The reason for this can be seen from Fig. 10.2. The sodium-altitude power spectrum falls steeply as frequency increases. In contrast, the power spectrum of NGS photon noise is flat. The change from NGS to LGS should thus be made when the two noise sources have comparable magnitude. Such a control system is under development for the TMT AO systems.

The spatial variations, determined from centroid velocity analysis as well as directly from the structure function as discussed in Section 10.4, result in differential focus errors between different LGS in an asterism. This compromises the ability of the AO system to sense differential atmospheric focus terms. Again, one must rely on NGS, but the number of such stars may be small. Conventional AO systems, and multi-conjugate AO systems (MCAO) employing two deformable mirrors (DMs) are unable to create differential focus modes, so these systems are not directly affected. However, future MCAO systems employing three or more DMs are susceptible to these errors and consideration of this will need to be taken in the design of their control systems. Similarly, multi-object AO systems (MOAO), which employ multiple DMs, must also be prevented from responding to these large differential focus errors.

Finally, we note that AO control systems will need be designed to tolerate the rapid transients caused by meteor trails. If ignored, these transients will saturate the WFS response, resulting in a loss of control system lock and an abrupt loss of Strehl ratio. They could be largely mitigated by designing the control system to ignore sudden large
transients in the WFS signals.

We are continuing to collect data with the lidar system in order to improve the quality of the results and to sample a wider range of atmospheric conditions. In view of the uncertainty in the physical origin of the high-frequency fluctuations, we plan to obtain direct measurements of horizontal structure functions by means of rapid chopping of the laser beam position on the sky, within the 1-arcmin field of view of our receiver, using a piezoelectric tip-tilt mirror. In addition to providing direct measurements to assist AO performance modeling, we hope that such observations will provide insight into the small-scale physics of the sodium region.
10.7 Relations Between Spatial Structure Functions of Sodium Density and Mean Altitude and the Temporal Power Spectra of Mean Sodium Altitude

We suppose that the sodium region contains density fluctuations being advected horizontally across the laser beam, with speed \( v(z) \), where \( z \) represents altitude. The sodium number density is \( n(x,z) \) where \( x \) is the position along the direction of advection, in the rest (Lagrangian) frame of the cloud. We denote fluctuations in density by

\[
n'(x,z) = n(x,z) - \langle n(x,z) \rangle, \tag{10.17}
\]

where the brackets indicate an ensemble average.

The sodium centroid altitude, at a given time and horizontal position, is defined by Eqn. (10.1)

\[
a = \frac{1}{N} \int_0^\infty nz\,dz \tag{10.18}
\]

where \( N \) is the vertical sodium column density. Small fluctuations \( \delta \rho \) in the sodium density thus give rise to altitude fluctuations

\[
a' = \frac{1}{N} \int_0^\infty n'z\,dz - \frac{a}{N} \int_0^\infty n'dz = \frac{1}{N} \int_0^\infty n'(z - a)\,dz \tag{10.19}
\]

Variations in mean altitude with horizontal position can be characterized by the structure function

\[
D_a(x) = \langle [a(0) - a(x)]^2 \rangle \tag{10.20}
\]
Substituting Eqn. \((10.19)\) into this gives

\[
D_a(x) = \frac{1}{N^2} \int_0^\infty dz \int_0^\infty dw(z-a)(w-a) \\
	imes \langle [n(0,z) - n(x,z)][n(0,w) - n(x,w)] \rangle 
\]

(10.21)

We now make the strong assumption that fluctuations at different altitudes are uncorrelated. This should be a fair approximation at least for fluctuations whose typical scales are much smaller than the characteristic width of the sodium region \((\sim 10 \ km)\). With this assumption, the quantity in brackets may be approximated by

\[
\langle [n(0,z) - n(x,z)][n(0,w) - n(x,w)] \rangle = D_\rho(x,z) \delta(z-w). 
\]

(10.22)

where \(\delta(z-z')\) is the Dirac delta function and \(D_\rho(x,z)\) is the structure function of sodium number density fluctuations at altitude \(z\). This gives

\[
D_a(x) = \frac{1}{N^2} \int_0^\infty D_\rho(x,z)(z-a)^2 dz. 
\]

(10.23)

At any altitude \(z\), temporal variations of density at a given point correspond to spatial variations along the wind direction according to \(x = v(z)t\). Thus, Eqn. \((10.23)\) gives rise to a temporal structure function of mean sodium altitude along the wind current direction:

\[
D_a(t) = \frac{1}{N^2} \int_0^\infty D_\rho[v(z)t](z-a)^2 dz. 
\]

(10.24)

This structure function is related to the temporal covariance \(C_a(t) = \langle a'(0)a'(t) \rangle\) by

\[
D_a(t) = 2 [C_a(0) - C_a(t)]. 
\]

(10.25)

By the Wiener-Khinchine theorem, the covariance is the Fourier transform of the (two-
sided) temporal PSD. Since the one-sided PSD, $P_a(v)$ has twice the amplitude, we have

$$C_a(t) = \frac{1}{2} \int_{-\infty}^{\infty} P_a(v) \cos(2\pi vt) dt. \quad (10.26)$$

Therefore,

$$D_a(t) = 2 \int_{0}^{\infty} P_a(v) [1 - \cos(2\pi vt)] dv. \quad (10.27)$$

For the power-law spectrum

$$P_a(v) = \alpha v^\beta \quad (-3 < \beta < -1), \quad (10.28)$$

Eqn. (10.27) gives

$$D_a(t) = \begin{cases} 2(2\pi)^{-\beta-1}\Gamma(\beta + 1)\sin(\pi\beta/2)\alpha t^{-\beta-1}, & -3 < \beta < -1. \\ 2\pi^2 \alpha |t|, & \beta = -2 \end{cases} \quad (10.29)$$

From this we see that the centroid altitude structure function is a power law with index $-\beta - 1$. To determine the sodium density structure function, we write

$$D_\rho(x) = C_{\rho}\rho(x)^{-\beta-1}, \quad (10.30)$$

where the proportionality constant $C_{\rho}(z)$, the structure constant of sodium density fluctuations, is assumed to be a slowly-varying function of altitude. Substituting this into Eqns. (10.23) and (10.24) gives

$$D_a(x) = \xi x^{-\beta-1}, \quad (10.31)$$

$$D_a(t) = \gamma t^{-\beta-1},$$

$$= \xi v^{-\beta-1} t^{-\beta-1}, \quad (10.32)$$
where

\[
\xi = \frac{1}{N^2} \int_0^\infty C_\rho^2(z)(z-a)^2 \, dz. \tag{10.33}
\]

\[
\gamma = \frac{1}{N^2} \int_0^\infty C_\rho^2(z)v(z)^{-\beta+1}(z-a)^2 \, dz. \tag{10.34}
\]

\[
\bar{v} \equiv \left( \frac{\gamma}{\xi} \right)^{\beta+1}. \tag{10.35}
\]

Combining Eqns. (10.29) and (10.32), we obtain

\[
\xi = \begin{cases} 
2(2\pi)^{-\beta-1}\Gamma(\beta+1)\sin(\pi\beta/2)\bar{v}^{\beta+1}\alpha, & -3 < \beta < -1, \\
2\pi^2\bar{v}^{-1}\alpha, & \beta = -2
\end{cases} \tag{10.36}
\]

For isotropic Kolmogorov turbulence, \( D_\rho(r) = C_\rho^2 r^{2/3} \) (Roddier 1981). Comparing this with Eqn. (10.30) we see that \( \beta = -5/3 \). Eqn. (10.28) now shows that Kolmogorov turbulence gives rise to a temporal power spectrum of mean sodium altitude that is a power law with index \(-5/3\).
Part IV

Conclusions
Chapter 11

Conclusions and Future Work

Two main topics have been presented in this thesis. The design and operation of lunar scintillometers as well as results were presented in the first half of the thesis. The design, implementation and operation of a lidar system for the liquid mirror telescope, to provide high spatio-temporally resolved sodium profiles from the upper mesosphere and lower thermosphere in support of extremely large telescopes (ELTs), is the second topic of this thesis. They both provide input to the decision and design process of next generation instrumentation.

11.1 Summary of Lunar Scintillometer Work

The atmosphere has been investigated to study optical turbulence in the lowest kilometer where local topography and meteorological influences produce image blurring. Each potential astronomical site has characteristic turbulence structure that can be revealed by a lunar scintillometer. Two instruments, the lunar scintillometers ATP and PTP, were designed, built and operated to investigate the ground layer turbulence at high spatial and temporal resolution on Mauna Kea, Hawaii and on Ellesmere Island in the Canadian High Arctic. A third instrument, the lunar scintillometer CTP, has been remotely operated for several years on Cerro Tololo in Chile.

More than 700 nights of ground layer data have been recorded from Cerro Tololo since 2007. The instrument operated semi-autonomously during three years of operation.
Experience in using this system enabled the design and operations of the next two scintillometers. The lunar scintillometer technique has been validated by cross-comparison of simultaneous observations with other instruments. Also, the fact that the measured quantities directly relate to the $C_n^2$-profile means that no calibration is needed and therefore, less systematic error is introduced.

The PTP in Hawaii has recorded ground layer turbulence regularly since May 2010, with 260 hours obtained from inside and outside the CFHT dome. Already this data set has revealed interesting results. While calm conditions with wind speeds less than 1.5 m/s provide the best seeing conditions according to the outside data, a lack of dome venting causes local turbulence from heat to form a turbulent wake outside the dome slit. In the absence of wind, this is stationary and results in the worst seeing condition for the CFHT 4-m telescope.

With wind entering the dome, venting is stimulated and seeing significantly improves, providing seeing conditions that are better than those measured outside. The high-resolution of the PTP in the ground layer also revealed outside-dome influence from flow detaching and causing turbulence in front of the dome slit in case of wind flow perpendicular to the observing direction. While these results may seem obvious in hindsight, the PTP, for the first time, is able to quantify these effects and reveal the spatial origin and contribution of each height to the optical turbulence in the ground layer. With this information, design changes to the CFHT dome will be guided to help improve the CFHT seeing to keep this very productive telescope at the forefront of science. Also, the design of İMAKA, CFHTs next-generation $1^\circ$ field ground layer LGS AO system, will profit from the high-resolution ground layer data and be optimized to Mauna Kea specific conditions.

The Arctic scintillometer (ATP) was designed and built in 2008-2009 and deployed in September 2009. Approximately 750 minutes of data were recorded during the first winter season in seven different days spread over two seasons. Ice accumulation, weather
and damage from a storm prevented us from acquiring further data. The data obtained so far has been analyzed and results were presented. These first results showed exceptional ground layer seeing conditions in the Arctic and with an assumed low free-atmosphere contribution similar to the Antarctic, the Arctic has the potential to be the best place in the world for astronomical observations at optical and infrared wavelengths. At the inland location of PEARL, with an elevation of only 600 m, the ATP data showed surprisingly low seeing values.

11.2 Summary of Lidar Work

In contrast to the low atmospheric region investigated by the scintillometer, one of the highest layers is of great importance to next-generation ELTs. To support the development of ELT AO systems, lidar measurements were needed to characterize the density distribution of the sodium layer with high spatial and temporal resolution. Before the UBC lidar project started, the best temporal sodium measurements sampled on timescales of minutes and spatial resolutions of order 100 m. In contrast, AO systems need information about the temporal structure change on the order of tens of milliseconds. The large light-collecting area of the LZT provided a perfect opportunity for such high-resolution measurements, so the lidar system was designed, built, tested and operated as part of this thesis. Sodium layer profiles are now provided in 20 ms time resolution and heights are recorded in bins of 3.6 m. Since summer 2008, data acquisition started and as of fall 2010, about 450 hours of data have been recorded. The lidar system is not remotely operated and physical presence at the LZT is required each night of observation, mostly because of safety requirements due to the powerful laser. The system itself is designed to operate without intervention throughout a nightly observing run, although spotters are needed to watch for aircraft. The main components of the new lidar system include the launch facility, receiver with counting electronics, data acquisition and software, beam
alignment system, aircraft surveillance radar and trigger and interlock system. They all need to work together, and be able to be controlled by one person in the control room. During routine operation, this is achieved and an experienced operator can startup the lidar within 15 minutes. If the weather permits, sodium data are recorded every clear night.

During 3 years of operation, a highly structured sodium layer was revealed, showing multiple layers varying in density and altitude on timescales of minutes to hours with small-scale turbulent features like Kelvin-Helmholtz billows as well as large-scale instabilities. The temporal power spectrum of the sodium centroid altitude extends above 1 Hz, and is well fitted by a power law having a slope of $-1.95 \pm 0.12$. Its deviation from the expected value of $-5/3$ (from Kolmogorov turbulence) is significant and suggests the influence of gravity waves. However with gravity waves only able to interact above the Brunt-Väisälä frequency, the slope would be expected to become shallower and thus more Kolmogorov-like on timescales smaller than $\sim 5$ min. This is not observed; in fact, no break in the power law is detectable over 4 decades in frequency. Doppler shifting of gravity waves by horizontal wind might explain this result.

These fluctuations produce focus errors in adaptive optics (AO) systems employing continuous-wave sodium laser guide stars, which can be significant for large-aperture telescopes. For a 30-m aperture diameter, the associated rms wavefront error is approximately 4 nm per meter of altitude change and increases as the square of the aperture diameter and thus, becomes a significant term in the adaptive optics error budget. Simulations with our profiles show however that adaptive optics can deal with such variations and that it will work. The rms vertical velocity of the sodium centroid altitude is found to be $\sim 23$ ms$^{-1}$ on a 1-s timescale. If these high-frequency fluctuations arise primarily from advection of horizontal structure by the mesospheric wind, our data imply that variations in the sodium centroid altitude on the order of tens of meters occur over the horizontal scales spanned by proposed laser guide star asterisms. This leads
to substantial differential focus errors ($\sim 10^7$ nm) over a 1 arcmin separation with a 30-m aperture diameter) that may impact the performance of wide-field adaptive optics systems. Short-lasting and narrow sodium density enhancements, more than an order of magnitude above the local sodium density, occur due to advection of meteor trails. These have the ability to change the sodium centroid altitude by as much as 1 km in less than a second, which could result in temporary disruption of adaptive optics systems. About 10 to 20 meteoric events are detected every hour, while only one to two meteor events per hour happen far enough from the sodium centroid and are strong enough to affect the centroid variation significantly.

### 11.3 Future Prospects

During this thesis, large data sets have been recorded for the lunar scintillometer and the lidar projects. While some results, indicating proper operation of all instruments, have been shown in this thesis, there are still data to be analyzed.

With the large data set, recorded on Cerro Tololo in Chile, the local turbulence structure can be studied in great detail and a $C_2^N$-profile analysis is possible leading to a determination of a general median ground layer turbulence profile. Monthly averages and a combined meteorology analysis, using prevailing wind information will allow studies of the influence of topography on optical turbulence, locally on Tololo, but also more general for mountain tops with similar exposure to the free streaming atmosphere, usually the case for astronomical mountain sites. This should contribute to an understanding of the effect of local flow patterns on optical turbulence, with the aim of improving the performance of optical telescopes.

The PTP data set showed very interesting results, especially from inside the dome. However, more data are needed. Routine observations are continuing from both, inside and outside the CFHT dome. With increasing data, the results will become more reliable.
While the inside data may help local induced seeing and İMAKA design considerations, the outside dataset will be used to compare with the CTP data to establish a general understanding optical ground layer turbulence.

The first season of observations with the ATP in the Canadian High Arctic was successful in terms of data quality, however data quantity was limited. This will hopefully be improved during the 2010/2011-winter season, which will then show if the first years exceptional GL seeing results are representative. This may be supplemented by DIMM measurements by the University of Toronto (R. Carlberg, priv. communication), which can probe the high atmosphere. With improvements to the ATP insulation we will also be able to evaluate its readiness for remote deployment. If all goes well, the ATP may be moved to a remote mountain top at the northern end on Ellesmere Island at 82.5°N and an elevation of ~1100 m.

The UBC lidar data have revealed the general dynamics within the sodium region and has provided an improved power spectrum of the sodium centroid altitude. This data set also enables us to study other useful parameters such as sodium width and column abundance, as well as peak densities. The annual variance of such parameters will be interesting to compare to other lidar sites. To study the influence of the ionosphere on the sodium layer abundance and its annual variation, the top of the layer and its shape and nightly variability is of interest. The nightly variability of the main sodium parameters will be studied through an hourly mean analysis, which will show dependencies of the sodium on the solar cycle and other diurnal relations. Apart from these main parameters the sodium layer has been analyzed with respect to spatial dynamics in the vertical direction. This yielded a power spectrum and its temporal evolution over the night. The study of the power index and normalization needs to be analyzed in detail to understand gravity wave interaction.

The rms difference between successive profiles is another useful parameter to analyze, because this is closely related to the AO matched-filter algorithms that need to update
their reference sodium profile, against the current return flux is compared. Such analysis will find the optimum time interval for updating the matched filter and will help in determining time constants in AO systems. The analysis of these parameters is already integrated in the main data reduction and analysis software, however more attention is needed to interpret the results. Interesting in this context is the analysis of simulated wavefront errors and its correlation with other parameters from the sodium layer. A principle component analysis may reveal possible correlation between nightly variations of different parameters, which will then be studied in more detail by correlation techniques. The result of such a study might be useful during routine AO observations because from basic sodium layer parameters and their variability, possible correlations to wavefront errors might be predicted and suitable AO corrections could be applied. And finally, a detailed statistical analysis of all parameters, important to AO, is underway to provide an understanding of the sodium layer not only on a nightly basis, but also on weekly and monthly variabilities and its effect on seasonal changes.

The high-resolution data also enable us to study the meteor influx function from the detected meteoric events that last from several 100s of millisecond to tens of seconds. Even small events are detected with enough signal-to noise ratio to stand above the local sodium density. A sophisticated search technique, based on 2D Fourier transform of the data has already been written and this analysis is underway. In the lidar data set we also see high density thin layers, which are attributed to sporadic sodium layers in the literature. Though they last on the order of hours and appear within minutes, AO systems are able to track such focal changes in the centroid and will likely not be affected in general by SSL. However, it is yet to be shown how variable these layers are and how often they occur at mid-latitudes.

The lidar data show a large variability on short time scales, and, assuming a constant mean wind, these results imply a potentially large wavefront error due to differential focus effects for multiple laser guide stars. Each LGS probes the sodium layer at slightly
different locations, about 30 to 100 m apart for the current AO designs for ELTs. To not rely on assumptions of the wind, we are in the process of implementing a tip/tilt mirror in the laser launch facility, enabling the beam to be steered within a 5 arcmin diameter on the sky. By probing the sodium layer at different locations, a spatial power spectrum in the horizontal direction can be obtained, and for the first time, horizontal information in high spatial and temporal resolution would be gained. In addition, such a study may reveal the three-dimensional wind pattern at high resolution throughout the sodium layer and as such the small-scale structure could perhaps be used to study the dynamics of the sodium layer at high resolution. This might help our understanding of the dissipation process of gravity waves and development of flow instabilities. By simulating an LGS asterism on the sky, experience will also be gained with a pulsed laser system similar to those that may be used in AO systems in the future to overcome the focus problem via spot tracking methods.

The lidar system at the LZT proved to be a valuable tool to help better understand sodium layer variabilities for the design of next generation ELTs, and will be used in the future for more detailed studies.


Bills, R. E., Gardner, C. S.: 1993, Lidar observations of the mesopause region temperature structure at Urbana, J. Geophys. Res. 98, 1011


Chesnokov, S. S., Skipetrov, S. E.: 1997, *Optical resolution through atmospheric turbulence with finite outer scale*, Optics Communications 141, 113


Hilborn, R. C.: 2002, Einstein coefficients, cross sections, f values, dipole moments, and all that, ArXiv Physics e-prints


Ivanescu, L.: 2010, “Clear sky evaluation over the Ellesmere Island using MODIS data at 1 km resolution”, (private communication)


density in the mesopause region (80 to 105 km) over Fort Collins, CO (41°N, 105°W), Geophys. Res. Lett. 27, 3289


Silva, D., Hickson, P., Steidel, C., Bolte, M. (eds.): 2007, TMT Detailed Science Case, TMT Observatory Corporation


Taylor, M. J., Hapgood, M. A., Rothwell, P.: 1987, *Observations of gravity wave propagation in the OI (557.7 nm), Na (589.2 nm) and the near infrared OH nightglow emissions*, Planetary and Space Science **35**, 413


Part V

Appendix
Appendix A

Detailed Sodium Layer Lidar Design

While in Chapter 8 the general design of the lidar was introduced, this appendix goes into more detail regarding the receiver design, its control and laboratory tests necessary to gain a detailed understanding of the system as well as to optimize every subsystem. This enabled us to obtain all results, shown in the result section of this thesis. After acquiring 150 hours of data with the first counting system, we upgraded the system to overcome some problems, that limited the system from counting all collected photons. In Section A.2 the first system is described, and in subsequent sections an outline of the new system is given.

A.1 Laser Launch Facility

The basic description of the laser launch facility and its subsystems has been given in Section 8.3.2. This section adds details to this short introduction.

A.1.1 Laser Conditioning Optics

The first design of a focused beam through a spatial filter has to be changed as the high power density at the focal position heats the air so strong that ionizing occurs. The resulting plasma consists of a sufficient high electron density that substantial laser power is removed from the forward beam through electron scattering in this focal plasma. One complicated solution to this issue would be to use a vacuum spatial filter. The other solution is to use a concave lens of the same focal length as the objective. With this setup
no spatial filtering can be done but because our requirements are not restrictive with respect to perfect beam on the sky, this solution was chosen. To calculate the correct focal length for the lens, we calculate the standard deviation $\sigma_f$ in the image is related to that of the pupil $\sigma_p$ by the Fourier optics

$$
\sigma_f = \frac{\lambda f}{2\pi \sigma_p}.
$$

(A.1)

where $f$ is the focal length of the concave lens. The launch telescope is a Takahashi TOA-150 refracting telescope with a 15 cm clear aperture ($d_{TOA}$) and a focal length of $f_t = 1100$ mm. We want the beam to fill the aperture of the launch telescope, but not loose photons at the corners. With the vertical extend of the beam, as it leaves the laser, to be 4.5 mm, the magnification of the system should hence be at most

$$
\frac{f_t}{f} = \frac{150}{4.5} = 33.3.
$$

(A.2)

This sets the focal length of the concave lens to commercially available -40 mm. The concave lens will be mounted on a translation stage, allowing the divergence of the output beam to be varied. With this set-up, we will be able to study saturation effects.

A.1.2 Optical Setup on the Table

The lasers, wavemeter, beam optics and launch telescope are positioned on the horizontal surface of an optical table. The table has dimensions of 3 m×1.2 m×0.3 m and is supported on pneumatic legs, whose air supply is provided through dry air from the main bearing compressor of the liquid mirror. Laser light from the dye laser is linearly polarized to about 98%. A beamsampler at 45° angle of incidence reflects 1% of linearly polarized light and guides it into the wavelength meter that has a maximum damage threshold of 1.5 mJ input energy per pulse. A custom Labview program has been written to control the wavelength. However, the wavelength drift is very slow in one night and it turns out to be more applicable to tube the dye laser by hand. This does not
happen more often than a few times per night at most. Fig. A.1 shows the setup on the optical table. After leaving the laser room horizontally, the beam travels above the 6-m mirror towards the opposite site of the main mirror room and a 2-axis motorized flat 10” mirror, mounted on a gimbal mount directs the beam upwards. This gimbal mount has motorized actuators, capable of positioning the beam within the specs of less than 1 arcsec. Only two mounting bolts are available in the concrete wall to secure the gimbal at this location. Fig. A.2 shows the chosen design for the gimbal mirror mount. The vertical tube, standing on the concrete floor of the primary mirror (1 m below concrete floor of the optical table, and hence about 2 m below the optical axis) is carrying the direct vertical force. Left- and right-hand threaded rod-ends on either end of the side tubes ensure horizontal alignment and stiffness.
Appendix A. Detailed Sodium Layer Lidar Design

Figure A.2: Gimbal mirror mount in the main room of the liquid mirror telescope.

A.2 First Counting System of the UBC Lidar Receiver

The general description of the first counting system has been given in Section 8.3.3. To control the PMT’s, a labview program has been written and is outlined in the following.

The block diagram of the setup in Fig. A.3 shows the relevant parts for the laboratory test and in red the most important control measures are given. Each PMT is hereby connected with a 20 pole cable to analog and digital I/O (input/output) devices from National instruments, which on their part connect to the computer via an USB connection. A custom LabVIEW program allows for easy control. Once power is provided, the control program allows cooling each PMT separately down to a preset operational temperature. Virtual LED’s that change from slow to fast blinking frequencies indicate the successful cooling phase for each PMT. High-voltage control can then be turned on and a dial allows us to adjust the high voltage inside the PMT’s and hence the appropriate gain. To allow the PMT signal to travel from the prime focus to the counting card, which covers
about 15 meters, it first has to pass a fast preamplifier and then a constant fraction discriminator (CFD) (Ortec 9327) to produce clean and fast NIM outputs (4 ns wide) that are strong enough to travel to the counting card in the computer. This stores the incoming pulses, after an external trigger start signal has been received, into bins, each 16 ns (2.4 m resolution in the sodium layer) wide. While in principle the card allows for a time resolution of 2 ns, the longer bins have been chosen to save disk space and because a higher resolution would not add more information from the sodium layer. The sodium excitation lifetime is 16 ns and as such each time bin would have to be convolved with this window function.

### A.2.1 The UBC Lidar Receiver Design and Laboratory Assembly

The lidar receiver is a custom mechanical design that hosts the optics to accommodate the f/1.6 beam from the primary LZT mirror, separates it into 4 paths and conditions and filters the beam to guide the photons, on the sodium wavelength to the diameter 5 mm small photo sensitive areas of the 4 PMT’s (see Fig. 8.3 for the ray tracing and
a more detailed explanation). Fig. A.4 shows the mechanical design with not all parts assembled for clarity reasons.

Before the receiver is installed at the LZT, extensive laboratory testing was carried out to ensure proper understanding of the hardware and software. Fig. A.5 shows the assembled receiver with attached PMT’s and all subsystems. In order to simulate the beam from the 6 m mercury mirror, having an effective f-number of 1.6, we are using a telescope simulator, designed by P. Hickson to test detector equipment for the CFHT, which gives a beam with an f-number of 2. This is a bit narrower compared to our fast beam. Therefore not the entire area of the collecting mirror quadrants will be used in this test. It is however very close to the actual set-up and allowed us to test the receiver and data acquisition system in a laboratory environment.

The optical setup is seen in Fig. A.6 where the telescope simulator is shown with a schematic radiation path that a sodium vapor lamp’s radiation will take, once entering through a pinhole.

In this simulator the light source, a sodium vapor lamp, shines into the vertical tube, a 50/50 pellicle beam splitter directs the light downward to a $\varnothing 15$cm f/1 spherical mirror. The entrance pinhole behind which the light source is located is 300mm away from the mirror. The beam passes through the beam splitter upwards and gets focused 300mm above the mirror surface, where the receiver focus is located. This 1:1 mapping of the pinhole insures the required beam specification. Between the simulator surface above the pellicle beam splitter and the focus plane a distance of 130 mm has to be maintained. To ensure exact position of the detector assembly, suitable spacers have been machined. The optical rail onto which the detector is mounted is attached to the translation stage on top of the LZT and positioned and secured on the spacers. All necessary components are mounted to the base plate. This includes the PMTs with the inlets responsible to hold the collimating optics, the ultra narrow bandpass filters as well as the focusing lens just before the photo cathode. The PMT’s temperature control/power supply unit sits
Appendix A. Detailed Sodium Layer Lidar Design

(a) Base plate with mirror base and chopper wheel plus motor. (b) View from above for a better look at the chopper wheel.

(c) Close-up look at the receiver heart where the PMTs will attach in star form on each wall. (d) Assembled PMT power supply and PMT with heat sink/fan. Only one of four is attached at that time.

(e) The receiver lid with its four outward-tilted 2° surfaces that will host the spherical mirror, cut into four quadrants. (f) Close-up look into the receiver from above, as seen from the quadrant mirror, to show the four 45° surfaces, hosting the elliptical flats.

Figure A.4: Mechanical design of the UBC lidar receiver.
Figure A.5: Lidar receiver in the laboratory, assembled with all PMTs on a telescope simulator with constant fraction discriminators, PMT power supplies and USB adapters for remote controlability.
Figure A.6: Schematic ray tracing of the optical receiver setup in the laboratory.
just above the PMT’s heat sink/fan on each of the four sides of the mirror mount of
the detector. From this unit the power cable with all necessary control connections as
well as the power cable to the fan, connects directly to the PMT. The necessary PMT
high voltage is produced inside the PMT unit and only low voltages up to 12 V and
1.2 A maximum are provided externally. The four control/power supplies are supplied
with 12 V from two 60 W AC/DC switching converters, each capable of offering 2 times
12 V at 2 A and 3 A. These two units are located under the base plate behind the rail.
A 110 V cable connects them together and one power cord, connected in parallel, is
responsible for supplying all necessary power to all PMTs (see Fig. A.3).

Each control/power supply unit of the PMT also connects the 20-pole cable to the
I/O devices, that are positioned on T-shaped aluminum mounts. The three I/O devices
allow for 48 digital I/O, 16 analog input and 4 analog output channels. Each of the four
PMT requires 8 digital, 1 analog in and one analog out channel. The digital connections
are used to control power, cooling power, PMT power, Peltier error signal, PMT error
signal and the respective monitoring LEDs. The analog out is used to adjust the input of
the PMT with the control voltage which sets the high voltage internally for gain control.
The analog in (of the I/O device) outputs the voltage that monitors the gain adjustment.

All three I/O devices are connected via USB to a hub, which will be located on the
prime focus of the LZT near the corrector optics. To allow for long USB connection, we
use a USB to fiber extension cable, transferring the PMT control signals over 15 m to the
control room where the back-conversion to USB takes place and plugs into the computer.

Signal cables from each PMT, 0.5 m BNC to BNC coax cables, are connected to the
input of the preamplifier/CFD units that sit on the platform of the base plate just above
the AC/DC converters. As the input connections are SMA, a BNC to SMA adapter is
used. These units are powered by their own power supply, connected via serial cables.
This 10 kg Ortec 4002 power supply unit is located under the prime focus platform on the
hexapod near the USB hub. The clean and strong signal is routed after the discriminator
Appendix A. Detailed Sodium Layer Lidar Design

Figure A.7: Full receiver setup with all subsystems operational.

via high quality 15m coax BNC to SMA cables to the fast counting PCI card in the computer in the control room.

The chopper wheel/motor unit, integrated in the detector mount, is connected via serial RS232 extension connection to the chopper control unit in the control room. Two short BNC cables are used to close the loop between synchronizer and control unit. The trigger input signal comes from a frequency generator, that will also trigger the counting card for the laboratory test. The actual trigger cycle for the telescope installation is described in Section A.3.1.

In total we need a 110 V power bar on top of the prime focus platform to connect four devices, which are the PMTs, the preamplifier/CFD units, the fiber cable and the hub. The described complete setup is shwon in Fig. A.7.
A.2.2 Test of the Receiver System in the Laboratory

To investigate and learn the response of the single components and to tune the CFD’s and PMT’s to their best performance, discriminator curves were recorded, dark current tests conducted and software tests performed. All measurements involving light have been performed with the chopper wheel turning at 50 Hz, stabilized with an external frequency generator. Fig. A.8 shows the complete setup in the laboratory with all subsystems and peripheral instruments.
Figure A.8: General test set-up
To control the PMTs via I/O devices a control software in Labview has been written, which provides a user interface and shows the status of each PMT at one glance. Its use is described in the following paragraph. After validating an error-free control/monitoring of the PMTs, the counting card was first tested with a simple function generator and square waves.

A low-pressure sodium spectral lamp, whose intensity is blocked by filters to accommodate signal levels, suitable for PMTs, is used to investigate the performance under realistic wavelength conditions. Absolute calibration but is not required. Especially the laser power on sky is not known to a precise level, so that absolute density sodium measurements cannot be performed with laboratory calibrated detectors. If calibration to absolute values is necessary in the future, in-situ measurements of Rayleigh light from atmospheric heights with known density, i.e. 45 km, is commonly used in the lidar community.

A.2.2.1 LabVIEW Virtual Instrument for PMT Control

This section outlines the assignment of the PMT control lines and their computer control.

Each PMT needs to have 5 digital IN, 3 digital OUT, 1 analog IN and 1 analog OUT channel. Each PMT provides one 5V external power (here used to show that power is on for a virtual LED \( \rightarrow \) ASS-POW) on the first digital OUT. Next, a digital IN is used for switching the peltier cooling on (\( \rightarrow \) Pel-POW), a digital OUT is used to show eventual errors by different blinking frequencies on a virtual LED (\( \rightarrow \) Pel-ERR). A PMT power switch as digital IN (\( \rightarrow \) PMT-POW) and a dig OUT again shows any errors (\( \rightarrow \) PMT-ERR). A LED, driven by a dig OUT shows if PMT power is on (\( \rightarrow \) PMT-LED) and an additional error LED (dig OUT) completes the possible error occurrences to make troubleshooting easier (\( \rightarrow \) ERR-LED). The last digital IN is used for an optional possibility to shut off the cooling fan (\( \rightarrow \) Fan-POW). This option is only possible to use for 5 minutes, before the fan starts automatically again. Also when a cooling error
occurs, the fan comes on automatically. The analog IN/OUT are used to monitor/control
the control the gain of the PMT (→ Vcont-MON and Vcont-EXT).

We have one digital I/O device with 24 channels (Dev1), and 2 devices (Dev2 and
Dev3) with each 8 digital I/O, 2 analog out and 8 analog in. Table A.1 shows the in
assignments on each device.

<table>
<thead>
<tr>
<th></th>
<th>PMT1</th>
<th>PMT2</th>
<th>PMT3</th>
<th>PMT4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASS-POW</td>
<td>Dev1:0.0</td>
<td>Dev1:2.0</td>
<td>Dev3:0.0</td>
<td>Dev2:2.0</td>
</tr>
<tr>
<td>Pel-POW</td>
<td>Dev1:0.1</td>
<td>Dev1:2.1</td>
<td>Dev3:0.1</td>
<td>Dev2:2.1</td>
</tr>
<tr>
<td>Pel-ERR</td>
<td>Dev1:0.2</td>
<td>Dev1:2.2</td>
<td>Dev3:0.2</td>
<td>Dev2:2.2</td>
</tr>
<tr>
<td>PMT-POW</td>
<td>Dev1:0.3</td>
<td>Dev1:2.3</td>
<td>Dev3:0.3</td>
<td>Dev2:2.3</td>
</tr>
<tr>
<td>PMT-ERR</td>
<td>Dev1:0.4</td>
<td>Dev1:2.4</td>
<td>Dev3:0.4</td>
<td>Dev2:2.4</td>
</tr>
<tr>
<td>PMT-LED</td>
<td>Dev1:0.5</td>
<td>Dev1:2.5</td>
<td>Dev3:0.5</td>
<td>Dev2:2.5</td>
</tr>
<tr>
<td>ERR-LED</td>
<td>Dev1:0.6</td>
<td>Dev1:2.6</td>
<td>Dev3:0.6</td>
<td>Dev2:2.6</td>
</tr>
<tr>
<td>Vcont-MON</td>
<td>Dev2:AI0</td>
<td>Dev2:AI2</td>
<td>Dev3:AI0</td>
<td>Dev3:AI2</td>
</tr>
<tr>
<td>Vcont-EXT</td>
<td>Dev2:AO0</td>
<td>Dev2:AO1</td>
<td>Dev3:AO0</td>
<td>Dev3:AO1</td>
</tr>
<tr>
<td>Fan-POW</td>
<td>Dev1:0.7</td>
<td>Dev1:2.7</td>
<td>Dev3:0.0</td>
<td>Dev2:2.7</td>
</tr>
</tbody>
</table>

*Table A.1: I/O device pin assignments to the four PMTs*

The control was in the LabVIEW environment and following two figures A.9 and A.10
show the user interface as well as the block diagram.
Figure A.9: User interface of the PMT Control Panel
After the power is provided to the PMT power supply and the LabVIEW vi runs, all four ASS-POW LEDs are illuminated. All other LED are off. Then the Peltier element can get switched on. The cooling LED blinks with a period of about 2 seconds. After a predefined temperature is reached (right now turned to -5 °C, which means the ambient temperature has to be within 5 °C to 30 °C), the slow blinking LED switches automatically to a fast blinking mode (0.5 s period). Now it is possible to turn the PMT power on which then changes the fast blinking LED to a steady on state. After these steps, the control voltage can slowly be increased up to the desired voltage. Control voltage can be monitored via the display, whereas the control voltage can be changed with the dial, or by typing in the last box.
Figure A.10: Respective block diagram to previous figure A.9
A.2.2.2 Discriminator Curves

Discriminators are used in electronic signal processing to separate wanted signal pulses from unwanted noise pulses. The quantity that divides signals from noise is the amplitude of the pulse. PMT’s usually output signal pulses of different amplitude, and to accurately measure the arrival time of the pulse, a simple threshold discrimination broadens the time resolution. A constant fraction discriminator (CFD) therefore electronically normalizes the arrival pulse and then determines the arrival time with a normalized threshold.

To understand the CFD response, a two-step process was chosen to set-up the right threshold levels on the discriminator. This process also includes the setup of the correct gain levels of the PMT, in order to amplify pulses (i.e. the number of electrons) resulting from photons, but not increase the noise too much, so that large noise pulses coincide with small signal pulses from photons.

The four PMTs have a gain range from 2 to $5 \times 10^6$. For a 50 Ω impedance cable and a pulse width of about 3 ns (checked with an oscilloscope directly at the PMT output) this translates to a mean pulse height for the PMT with the highest gain of about -20 mV. The preamplifier/CFD units can either be used in a high gain mode (input level from 0 to -30 mV) or coarse gain (up to -150 mV). We decided to use the high gain after several tests. In order to match the different pulse heights from different PMT’s due to their different gain levels, an additional adjustment can be made at the preamp input connection to more finely control the pulse height within a small range. Setting the discriminator threshold determines the voltage level that is considered to result from a photon incident. Thus we separate noise counts from photon counts. Discriminator curves have been recorded that will identify the correct gain level. The discriminator cannot be controlled remotely, and hence a chosen setup was set for the receiver before installation on the prime focus, where it is not easily accessible anymore. The common sense to determine the threshold level is that a pulse is considered countable if it rises...
Figure A.11: Discriminator curves for all four PMT/preamp/CFD setups at -5 °C

significantly above the noise level. At a low threshold, counts are seen from noise as well as from photons. With rising threshold, the noise level significantly drops, while the counts from photons stay rather constant, and a discriminator curve flattens with rising threshold until the threshold gets too high so that even the strongest pulses from photon counts fall under the threshold and the curve goes eventually to zero. This did not happen in our case, as the discriminator threshold adjusting level only ranges from -10 mV to -1.0 V. Fig. A.11 shows the discriminator curves for each PMT with several PMT gain settings, and the chosen threshold level and gain setting is indicated. The thermoelectrical cooling level for all PMT’s was set to -5°C.
For PMT 3 and 4, another level at higher count rates could also have been chosen (around 0.9 V control voltage for the PMT gain and -0.2 V CFD threshold), but because Hamamatsu gives the same cathode sensitivity for all four PMT's, about the same count rates should be achieved. An interesting feature was noticed while adjusting the threshold and testing different fine gain levels with the help of an oscilloscope. Exactly after 20 ns, another output pulse from the discriminator has been generated. We first thought that this issue was due to ion events (resting atoms in the tube get ionized by fast electrons and accelerated towards the cathode) that create larger pulses, causing the discriminator to give a second pulse. This would however have meant the discriminator would have a dead time of 20 ns and not the specified <10 ns. A deeper investigation with the counting card triggered on the pulse, and comparison of peak heights between the 0 ns and 20 ns pulse showed a clear dependency to different threshold levels, but not as it would happen from ion pulses. This turned out to come from reflections in the signal cable, that just happened to have the right length to produce under certain conditions a second pulse. We therefore changed the cable length to the shortest possible length of 0.3 m, and this issue went away.

A.2.2.3 Dark Counts

After the threshold was set, it was of interest, if the dark counts show the same low level as indicated by the company that made the PMTs, Hamamatsu. Dark counts are counts that arise from thermal emission of electrons by the photo cathode. They are accelerated and amplified as are electrons resulting from photon events. Fig. A.12 shows the result, and with a control voltage setting of 0.9 V, even the worst PMT provides less than 2 photons per 20 ms, the repetition rate of our system. Taking into account that we are counting photons within a time window of 300 µs, the range of arrival times of photons from the sodium layer, dark counts are negligible. Other noise sources that might play a role, besides the dark counts, could be dynode thermal emission, 1/f noise from the
After the installation of the receiver at the LZT, the trigger system was installed. The mechanical chopper is the least accurate device that needs to be synchronized with the laser. It will therefore be before all crucial devices in the trigger chain. To avoid interference of the counting electronics with the surveillance radar, this system is also included in the trigger cycle. In fact it starts the trigger, because it uses a 600 Hz repetition rate. The pulse signal from the radar is divided by 12 in a custom-soldered electronic box by P. Hickson to get the nominal 50 Hz repetition rate for the laser, and connected to the synchronizer of the chopper wheel, which runs an internal closed loop control system. This signal is then used to trigger the laser, which in turn triggers the counting system. In addition, the laser is also capable of triggering the wavelength meter.
Appendix A. Detailed Sodium Layer Lidar Design

A.3.2 Aircraft Surveillance Radar, Laser Interlock and Thermally Insulated Laser Room

A.3.2.1 Aircraft Surveillance Radar

As per Transport Canada requirements, a radar is required to detect approaching aircraft and automatically turn off the laser, as indicated in Section 8.3.4.

The transmitter is a Furuno 1942 Mark2 6 kW X-band (9.4 GHz) marine radar. The rotating bar antenna was replaced with a feedhorn to provide zenith-pointing surveillance capability to detect aircraft at heights up to 14 km. Our horn has a gain of $\sim 23$ dB on axis and the lobes fall off to $\sim 20$ dB at about 12° full beam width (compared to 21° in E- and H-plane of the Dalhousie system). The original rotating antenna generates a square wave signal at 450 pulses/rev (180 Hz given 24 rpm) as well as a reset pulse once per revolution to the display. As we removed the antenna and gearbox, these pulses are no longer available. A frequency generator was therefore installed by the UBC electronics shop to provide the required 180 Hz, and a second signal at 0.4 Hz (1 puls/rev) simulates the reset. The radar receiver electronics provide an open collector output for an external alarm. This was connected to our interlock system to automatically shutdown the laser in case an aircraft or other object enters on top of the radar.

The radar was mounted 2.5 m above the primary mirror level, 1.6 m from the control room wall and 0.8 m from the sidewall. This setup does not interfere with the field of view of the prime mirror and allows a $\pm 25^\circ$ divergence angle of the radar beam to each of the observatory walls, which corresponds to -17 dBi in the E-plane and -23 dBi in the H-plane. The sensitivity adjustment of the radar system ensures no false alarms. The alarm zone is set to a range from 0.15 to 7.5 nautical miles (NM).

The system was tested by means of fly-over tests using a private single-engine aircraft. The aircraft was flown directly over the observatory at altitudes ranging from 600 ft
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to 5100 ft above the observatory. The altitude and ground speed was provided by on-board instruments (WAAS GPS). By timing the duration of the alarm signal, and comparison with the altitude and ground speed of the aircraft, the cone angle of the area of sensitivity was determined and found to be $\pm 15^\circ$ at all altitudes within measurement errors. Table A.2 shows the results from the fly-over test. Alarm time indicates the duration within the area of sensitivity. The ground speed was on average 90 $\pm$ 5 knots.

Altitude is above sea level $\pm$ 50 ft. The observatory is located at an altitude of 1400 ft (400 m). The measured range indicates the radar height as determined using a cross hair cursor on the radar screen. In addition to these tests, commercial jet transport aircrafts that came within the cone of sensitivity were detected. These aircraft showed measured ranges from 1 to 1.5 nm, consistent with their transition altitudes on the instrument approaches into Vancouver International Airport. They triggered the alarm 4 seconds before passing over the observatory. Since the laser shutdown is instantaneous, there is no possibility of an aircraft flying through the laser beam.

Table A.2: Fly-over tests of the radar system

<table>
<thead>
<tr>
<th>Pass</th>
<th>Altitude MSL [ft]</th>
<th>Measured range [NM]</th>
<th>Alarm time [s]</th>
<th>Horizontal alarm time [NM]</th>
<th>Half angle opening [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>0.25</td>
<td>6</td>
<td>0.15</td>
<td>14</td>
</tr>
<tr>
<td>2</td>
<td>2500</td>
<td>0.30</td>
<td>8</td>
<td>0.20</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>0.37</td>
<td>10</td>
<td>0.25</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>3500</td>
<td>0.38</td>
<td>10</td>
<td>0.25</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>4000</td>
<td>0.55</td>
<td>12</td>
<td>0.30</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>4500</td>
<td>0.63</td>
<td>14</td>
<td>0.35</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>5500</td>
<td>0.83</td>
<td>15</td>
<td>0.38</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>6500</td>
<td>0.98</td>
<td>18</td>
<td>0.45</td>
<td>13</td>
</tr>
<tr>
<td>9</td>
<td>4500</td>
<td>0.63</td>
<td>16</td>
<td>0.40</td>
<td>18</td>
</tr>
</tbody>
</table>
A.3.2.2 Laser Room

The optical requirement of having a stable temperature of $20^\circ\text{C} \pm 3^\circ\text{C}$ required us to build a separate, insulated, room within the telescope building. This room is equipped with an airlock entrance for insulation and dust control. The airlock also provides a convenient location for environmental suits and laser goggles. The laser room is $16' \times 8' \times 8'$ in dimension, which gives adequate clearance around the $4' \times 10'$ optical table. It is equipped with a heat pump and an HRV (Heat Recovery Ventilation) system that maintains a constant temperature. The heat pump cassette is located in the centre of the ceiling to provide uniform heating and cooling. Two additional diffusers with a venting system are also located on the ceiling. An oversized duct system insures low air speed that should not disturb the laser beam on the optical table. A chiller, used for cooling the Nd:YAG pump laser is installed outside the room on vibration isolator spacers to reduce vibrations on the floor. Fig. A.13 shows the set-up with the water-cooling chiller outside the room beside the airlock. The room is equipped with an interlock system to meet safety requirements. The radar, as well as the flow-meter, which measures the water temperature and flow rate.
of the pump laser, are connected to the system. In case of an interlock event (an aircraft entering the radar zone, low flow rate, hot water temperature), the system automatically shuts down the laser. The radar display is located in the telescope control room. If an aircraft enters the surveillance area, an alarm sounds and instantly closes a relay, which opens the interlock circuit. The electronics, developed by P. Hickson, are located in the rack mount in the control room, where there is also a red push button that enables us to manually shutdown the laser in case of an emergency. An arm/disarm system and LASER ENABLED warning light is located just outside the laser room and connected to the interlock circuit. The warning light employs third generation blue LEDs so as to not interfere with our high sensitive photomultipliers at 589 nm. Their emission spectrum was measured, and no emission was detected on the sodium wavelength.

A.3.3 Beam Alignment System

In order to ensure that the laser beam is directed exactly at the zenith, and therefore centered in the field of view of the 6 m telescope, a sighting telescope was installed. This is a Celestron C6 with a 6" aperture and a f/10 ratio, equipped with a sensitive B/W CCD detector (SONY ICX424). The CCD pixel size of 7.6 \( \mu \)m provides a resolution of 1.5 arcsec and a field of view of 11 arcmin. This telescope is mounted to the LZT structure and aligned to the vertical axis using a precise bubble level (1 arcsec resolution). Positioning of the laser beacon on the sky is done manually by driving the motorized actuators of the gimbal mount with visual inspection using a real-time CCD display. The separation between the Rayleigh scattering (which tops at about 60 km height) and the sodium beacon at \( \sim 92 \) km will be of the order 10 pixels on the alignment CCD. The image of the laser beacon as well as star trails are seen in Fig. A.14. This long exposure image with 30 sec integration time also revealed the sodium spot, indicated on the figure, besides the pronounced Rayleigh beacon. Using star trails as calibration source and applying the sidereal rate at the latitude of the LZT with 9.81 arcsec/sec gives the pixel scale and
Figure A.14: Rayleigh backscatter and sodium spot with 30 sec exposure. Star trails and sidereal rate are used to calibrate the pixel scale.
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hence the angular extent $\sigma_B$ of the laser beacon of $4.5 \pm 0.5$ arcsec. Assuming an average seeing $\sigma_\varepsilon$ at the LZT of $2.5 \pm 0.5$ arcsec and assuming Gaussian beams for the laser as well as for the seeing disc reveals the actual extent in the sodium layer after a deconvolution to $\sigma_L = 3.7 \pm 0.9$ arcsec or $1.8 \pm 0.4$ m at 90 km height. The errors are assumed errors, and the cumulative error is given using error propagation. Having a 12 cm collimated beam leaving the laser launch facility, diffraction will widen the beam until the sodium layer is reached, to 43 cm. With the Fried parameter much less than 10 cm as it is for the best astronomical sites, this beam is also affected by optical turbulence in the air and 2.5 arcsec seeing blurs it further to 1.2 m. The discrepancy of the last 40 cm between the theoretical beam size at the sodium layer and the actual measured beam size can be explained with power broadening, which means we are saturating the center of the beam and therefore apparently enhancing the wings of the laser beam compared to the center.

A.4 New Counting System of the UBC Lidar

With the first generation counting set-up, counts were limited due to signal throughput in the counting card. This counting system is only able to count at GHz count rates for burst times lasting less than 4 $\mu$s. Continuous photon counting is only possible at 20 MHz per channel, the clock speed of the PCI bus. The other disadvantage of this counting system is that after 3 min of data acquisition, all data needs to be transferred from the on-card memory to the computer hard disk. This takes time and during the transfer no new data can be stored. The transfer takes about 16 sec, before a new 3 min high-resolution set of sodium profiles can be acquired. This disadvantage was corrected with the procurement of a different counting system, not available at the time of the design and procurement start of this project. Sodium data from the start of this study in July 2008 to the end July 2009 is acquired with the first generation counting system and afterwards the new system was used, see Section A.6 for a data collection summary.
Figure A.15: The compact new counting system, installed on the prime focus since August 2009.

Another advantage of this new system over the first generation – apart from the ability to detect and count uninterrupted time series of data – is, that it incorporates a very fast discriminator card. The dead time of these discriminators is given by the company Sigma Space with 2 ns. Compared to the \( \sim 10 \) ns for the Ortec CFD’s from the first generation system, this provides an improvement in photon counts as coincidence losses are reduced. The custom-made system is very compactly designed in a box 200 cm\( \times \)280 cm\( \times \)10 cm and does not rely on a PCI bus clock. In fact the counting card is incorporated after the discriminator card, together in a stand-alone system and continuous data flow from the system, located on the prime focus near the receiver via USB 2.0 connection to the data acquisition computer ensures uninterrupted data acquisition. Fig. A.15 shows the compactness and internal electronics of the new counting system. A special USB extension cable is used to span the long distance between data acquisition and data.
storage. The use of two USB ports on the computer side provides enough power to extend the signal loss-free from the prime focus down to the acquisition computer. At the prime focus, short 30 cm coaxial connection between the PMT and the counting system prevent false double counts of reflected photon impulses at the SMA connection of the counting system. Before the system was used, the setting of the discriminator levels was checked and verified via new discriminator curves. Compared to the first generation counting system, the data format of this system includes a header for each pulse that – after a refurbishment – provides information about the bin size setting. Another very useful feature is that two different bin sizes can be chosen. This enables us to record Rayleigh scattering above 45 km at a coarse resolution and subsequently after a set number of bins, the sodium layer, above 75 km with fine resolution. The simultaneous data acquisition of Rayleigh scattering and sodium layer allows for an absolute calibration of photon counts to sodium density with the assumption of a non-disturbed standard atmosphere at the height of Rayleigh backscatter acquisition. Another assumption is that the sodium layer is not saturated, which, in our case, is most likely not true. The control of this system is established via the already mentioned USB connection on the acquisition computer that runs the control software.

A.5 Sodium Layer Return Flux

To calculate the return flux, the lidar equation 4.1 introduced in Section 4.2.1 can be used. A detailed calculation for continuous wave (cw) lasers can be found in Holzlöhner et al. (2010). This study uses Bloch equations and accounts for the magnetic field vector, as cw lasers employ a very narrow laser spectrum with widths around a few MHz and therefore only excite one hyperfine transition in the sodium atom. It is thus important to investigate possible relaxation paths in the energy level diagram, which is split into magnetic quantum numbers, in order to understand and optimize the excitation
process on the preferred hyperfine transition (Moussaoui et al., 2009). Polarization is another very important parameter in this study. Pulsed lasers, however, employ a much wider frequency spectrum whose envelope over the single excited modes shows widths of \( \sim 1.2 \) GHz. A large fraction of the Doppler-broadened sodium hyperfine spectrum of the D\(_2\)-line (see Section 4.2.2 for details) is therefore used to excite many velocity classes in the Doppler-broadened absorption coefficient spectrum. The length of the laser pulse, a few ns, is comparable to the excitation lifetime of sodium and the repetition rate (50 Hz) is low compared to the collision rate in the sodium layer. The weighted collision rate for sodium atoms with air particles is \( \sim 600 \) Hz, as stated in Holzl{"o}hner et al. (2010). Depopulation and non-equilibrium effects like Larmor precession and recoil from radiation pressure are therefore not important. However with an average laser power of \(~ 5\) W, the power per pulse is very high (\(~ 17\) MW), and saturation effects have to be considered. Only about 800 kg of mesospheric sodium exists globally, if one uses a general column density of \( 4 \times 10^{13} \) m\(^{-2}\) at a height of 92 km. It is hence a rarified species, with air particles \( 10^8 \) times more abundant. This relatively high air density, compared to sodium, is however not enough to expect significant backscatter signal from Rayleigh-scattered photons. With a nominal average laser power of 5 W and a repetition rate of 50 Hz, every shot has an energy of 100 mJ. With 6 ns long pulses, which is justified by measurements from the Dye laser company Sirah, see Fig. A.16, this translates into a pulse power of 17 MW. While the average time evolution of a pulsed laser looks similar to that shown in Fig. A.16, the electric field for a single shot has a time variation proportional to the Fourier transform of the field in the frequency domain. In the resonator, about 3\pm 1 modes are excited, each separated by about 500 MHz and with a width of about 50 MHz. 100 mJ at 589 nm means that in every shot \( 3 \times 10^{17} \) photons are produced. Transmitter optics, including beamsampler, folding mirror, ocular lens and gimbal mirror, have an 87\% overall transmittance. The atmosphere is estimated with 80\% transmittance, so that we have 60\% uplink efficiency. Thus, about \( 2 \times 10^{17} \) photons arrive at the sodium layer.
With a generally accepted mean column density of $4 \cdot 10^{13}$ m$^{-2}$ \cite{Plane2003}, and a 1.5 m diameter beam, $7 \cdot 10^{13}$ sodium atoms are illuminated. With the absorption cross section spectrum, derived in Section \ref{sec:4.2.2}, a general absorption cross section of $\sim 6 \cdot 10^{-16}$ m$^2$ can be calculated. Multiplying the absorption cross section with the column density gives an absorption probability of $\sim 2.5\%$. This indicates that we are heavily saturating and a special care needs to be taken to understand the return flux under such conditions. The volume absorption rate $r_{12}(v)$ in units of absorbed photons per second per volume per unit frequency interval $d\nu$ from the ground level 1 to an excited level 2 in an atom with a normalized absorption line shape $g(v)$, is defined as

$$r_{12}(v)dv = n_1 B_{12} g(v) J_v(v)dv \quad ,$$

(A.3)

where $n_1$ represents the number density of atoms in the ground level, $B_{12}$ is the Einstein absorption coefficient and $J_v(v)$ is the mean specific intensity of the incoming light pulse, directed into the solid angle $d\Omega$,

$$J_v(v) = \frac{1}{4\pi} \int I_v(v) d\Omega \quad .$$

(A.4)
\( I_\nu (\nu) \) is the specific intensity. \( J_\nu (\nu) \) has units of power per unit area per unit frequency interval per steradian. The Einstein coefficient \( B_{12} \), if defined as in Eqn. A.3, has units of area times frequency per unit power per unit time. The laser line shape is assumed to be independent of the laser power per solid angle \( P_\Omega \), hence the mean specific intensity with normalized line shape \( f(\nu) \) and illuminating an area \( A \), can be written as

\[
J_\nu (\nu) = \frac{f(\nu)}{4\pi A} \int P_\Omega d\Omega \quad .
\]  
(A.5)

The number density \( n_1 \) on the right hand side of Eqn. A.3 can be integrated over the width \( L \) of the sodium layer with path length \( ds \), resulting in a column density \( C_{Na} \):

\[
C_{Na} = \int n_1 ds \quad .
\]  
(A.6)

The volume absorption rate was defined as the absorption rate \( R_{12} \) within the illuminated volume \( L \cdot A \), so that it follows that

\[
r_{12} = \frac{R_{12}}{L \cdot A} = \frac{C_{Na} B_{12}}{4\pi A \cdot L} \int g(\nu)f(\nu)d\nu \int P_\Omega d\Omega \quad .
\]  
(A.7)

Thus, defining the return flux quantity \( \psi \) with units \( \text{ph/sec/srad/W/(atoms/m}^2\) and integrating the laser power \( P_\Omega \) over the solid angle, resulting in \( 4\pi P = \int \Delta \Omega P_\Omega d\Omega \), with \( P \) being the laser power, leads to

\[
\psi = \frac{R_{12}}{P \cdot C_{Na} \Delta \Omega} = \frac{B_{12}}{4\pi} \int g(\nu)f(\nu)d\nu \quad ,
\]  
(A.8)

because in order to get the return flux in units of steradians, we divided both sides of Eqn. A.8 by \( 4\pi \). Note that both line shape functions \( g(\nu) \) and \( f(\nu) \) are normalized with

\[
\int g(\nu)d\nu = \int f(\nu)d\nu = 1 \quad ,
\]  
(A.9)

and hence have each units \( 1/\text{Hz} \). To equate the absorption rate with the return flux from Eqn. A.8 has been used with the assumption that stimulated emission can be neglected,
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and all absorbed photons are isotropically emitted with spontaneous emission. The 6 ns long coherent pulse and 16 ns long excitation lifetimes don’t induce much stimulated emission. Eq. A.8 can be further modified, with $A_{21}$ as the Einstein spontaneous emission coefficient and the $g$-factors $g_1$ as multiplicities for the two levels 1 with multiplicity $2J_1 + 1 = 2$ and 2 with $2J_2 + 1 = 4$ (see Section 4.2.2). Using

$$B_{12} = \frac{g_2}{g_1} \frac{c^2}{2 \hbar \nu_0^3} A_{21}$$

(A.10)

with $\nu_0$ being the line center frequency of the transition and

$$A_{21} = \frac{g_1}{g_2} \frac{2\pi q^2}{\varepsilon_0 m_e c^3 \nu_0} f_{abs},$$

(A.11)

where $f_{abs}$ is the absorption oscillator strength, $q$ the electron charge, $m_e$ the electron mass and $\varepsilon_0$ the permittivity in vacuum, leads to the return flux in terms of the absorption oscillator strength

$$\psi = \frac{1}{4 \varepsilon_0 m_e c \hbar \nu_0} f_{abs} \int g(v)f(v)dv.$$  

(A.12)

The absorption line shape has already been calculated in Section 4.2.3 (see Fig. 4.5) and the laser line is treated next. This following paragraph is following an unpublished report from P. Hickson.

In general, the laser line shape has already been introduced with Fig. A.16, that shows in the time domain the result of beating modes for one pulse. The width of each mode in the frequency domain can be derived from ther Fourier transform of the time evolution of the pulse. Assuming a Gaussian beam with FWHM of $\tau = 6$ ns, the mode width $\Delta \nu_{mode}$ is

$$\Delta \nu_{mode} = \frac{2 \ln(2)}{\pi \tau} = 73.5 \text{ MHz}.$$  

(A.13)

From the laser company, we know that the modes, excited in the laser resonator, are separated by $\Delta \nu_{sep} \approx 450 \text{ MHz}$ and the envelope of the overall laser line is Gaussian with a FWHM in frequency space of $\Delta \nu_{env} \approx 1.2 \text{ GHz}$. Thus the laser line shape, assuming
Gaussian distributions for each mode, can be modelled as

\[
  f_\nu(\nu) = \exp \left[ -4 \ln(2) \frac{(\nu - \nu_0)^2}{\Delta \nu_{env}} \right] \sum_j \exp \left[ -4 \ln(2) \frac{(\nu - \nu_0 - j\Delta \nu_{sep})^2}{\Delta \nu_{mode}^2} \right] .
\]  

(A.14)

With this definition, the integral over the line shape is 1. If we want the integral to represent the total energy per pulse, we need to multiply Eqn. (A.14) by the energy on the line center \( f_\nu(0) \), such that the integral becomes 0.1 J, the output energy per pulse of the UBC laser. The numerical value in the line center calculates to \( f_\nu(0) = 4.512 \times 10^{-10} \text{JHz}^{-1} \).

To calculate the saturation effect on the line shape and the return flux, we consider an excitation process with one sodium atom. Its Doppler-broadened line has been calculated, and the probability that an incoming laser atom excites the atom is proportional to the specific surface energy density \( F_\nu(\nu) \) in case of a low-power application. Its difference to the previously calculated specific energy \( f_\nu(\nu) \) is that we are additionally now assuming a spatial Gaussian distribution with FWHM of \( d = 1.5 \text{m} \) being illuminated by the laser beam:

\[
  F_\nu, r = f_\nu(\nu) \frac{\ln(2)}{\pi (d/2)^2} \exp \left[ -4 \ln(2) \left( \frac{r}{d} \right)^2 \right] \\
  = \ 0.392 f_\nu(\nu) \exp \left[ -1.23 r^2 \right] .
\]  

(A.15)

If we had an infinite number of atoms in the ground layer, the number of excited atoms after an incoming laser pulse is directly proportional to the number of laser photons. We do not have an infinite number of atoms, in fact the number of atoms to be excited is much smaller than the number of provided laser photons. Thus every excitation process takes away an atom to be excited from the other ensemble laser photons, and hence the initially direct proportionality needs to be adjusted to account for saturation effects. With the proportionality constant set to \( \alpha \), the differential probability of an atom being excited can be written as

\[
  dP(\nu) = [1 - P(\nu)] \alpha dF_\nu, r(\nu) .
\]  

(A.16)
Integrating Eqn. A.16 results in

$$P(\nu) = 1 - e^{-\alpha F,\nu(v)} .$$  \hspace{1cm} (A.17)

We need now to determine the factor $\alpha$. Its unit are area times frequency per Joule.

From previous discussion we know that $\alpha$ should be closely related to the absorption cross section. The only difference is, the product $\alpha F,\nu(v)$ needs to be dimensionless.

Following an argument by [Hilborn (2002)], we can write the power $-\Delta \chi_p$ per steradian, being absorbed due to laser illumination in the frequency interval $\nu$ to $\nu + d\nu$, as

$$-\Delta \chi_p = h\nu_0(B_{12}/4\pi)g,\nu(v)I(\nu)N_1 d\nu d\Omega .$$  \hspace{1cm} (A.18)

$I_\nu$ is the intensity, confined to the perpendicular area $A$, lost from the beam by its pass over a distance $\Delta s$,

$$-\Delta \chi_p = h\nu_0 B_{12} 4\pi g,\nu(v)I(\nu)n_1 d\nu A \Delta s d\Omega .$$  \hspace{1cm} (A.19)

Thus, with the change in power per cross sectional area $A$ and frequency intervall $d\nu$, $\Delta \chi_p/(Ad\nu)$, being the change in intensity $dI_\nu(v)$ over the path $ds$, leads to

$$\frac{\Delta \chi_p}{Ad\nu d\Omega} = \frac{dI_\nu(v)}{ds} = -h\nu_0 n_1 B_{12} 4\pi g,\nu(v)I_\nu(v) .$$  \hspace{1cm} (A.20)

With the definition of the absorption coefficient $\alpha_{\nu,s}$ (in units of $m^{-1}$)

$$\frac{dI_\nu(v)}{ds} = -\alpha_{\nu,s} I_\nu(v) ,$$  \hspace{1cm} (A.21)

we can write

$$\frac{1}{I_\nu(v)} \frac{dI_\nu(v)}{ds} = -\alpha_{\nu,s} = -h\nu_0 n_1 B_{12} 4\pi g,\nu(v) .$$  \hspace{1cm} (A.22)

Dividing $\alpha_{\nu,s}$ by $n_1$ gives the absorption cross section $\sigma_{\nu,s}$ in units of $m^2$. To become the total absorption we need to integrate over the absorption lineshape $g,\nu(v)$, thus the absorption cross section becomes now $\sigma_s$ in units of $Hzm^2$. The defintion of the
proportionality constant $\alpha$ in Eqn. A.17 can now be related to a physical quantity, the modified absorption cross section per energy, if we divide $\sigma_s$ by $h\nu_0$,

$$\alpha = \frac{\sigma_s}{h\nu_0} = \frac{\alpha_s}{h\nu_0 n_1} = \frac{B_{12}}{4\pi} \int g_\nu(v)dv = \frac{B_{12}}{4\pi}.$$  \hspace{1cm} (A.23)

The surprising result is that the proportionality constant is the Einstein absorption coefficient over the solid angle $B_{12}/4\pi$. Converting $B_{12}$ into the absorption oscillator strength $f_{abs}$ gives

$$\alpha = \frac{B_{12}}{4\pi} = \frac{1}{4\epsilon_0} \frac{q^2}{m_e c} f_{abs} = 5.04 \cdot 10^{12} \text{m}^2\text{Hz/Ws}.$$  \hspace{1cm} (A.24)

But because our laser spectrum (in low power non-saturation mode) does not fill out the entire absorption spectrum but only $\sim 8.5\%$, $B_{12}$ has to be multiplied with this percentage. So evaluating the probability of an excitation (Eqn. A.17) on the line center at $\nu_0 = 5.08849 \cdot 10^5$ GHz gives with Eqn. A.15 $P(\nu_0) = 1 - \exp[-0.392(B_{12} \cdot 0.085/4\pi)f_\nu(0)]$, it is essentially 1, thus each atom with no velocity component in the laser direction is being excited on the line center. The situation for the total Doppler-broadened ensemble cross section of sodium atoms is shown in Fig. A.17. Thus, with the laser tuned to obtain optimal return flux, 45% of the $7 \cdot 10^{13}$ atoms in the 1.5 m diameter cylinder with column density $4 \cdot 10^{13}$ m$^{-2}$ are excited and are spontaneously emitting photons into $4\pi$ steradian sphere. Hence at a 6 m mirror 90 km away from the scattering process, the collection probability is $2.8 \cdot 10^{-10}$. With a transmission in air of 0.8, $6 \cdot 10^3$ photons arrive on the mirror. The receiver transmittance is, taking mercury reflectivity of 78% into account, 60%. The photon multiplier tubes (PMT) have a sensitivity of 174 mA/W. Each photon produces therefore on average a charge of sensitivity times energy per photon, hence $5.9 \cdot 10^{-20}$ As, which, with the elementary charge $q = 1.6 \cdot 10^{-19}$ As, translates into a quantum efficiency of 37%. So roughly each third photon actually produces an electron that can be accelerated and amplified in number in the PMT. This results in
Figure A.17: Absorption cross-section with hyperfine components of the Sodium D2-line with conditions at the sodium layer height. The laser modes are shown, normalized to 1 on the line center and the excitation probability is overplotted. Due to the extensive laser power, strong spectral power broadening occurs, which means that the wings of each laser mode excite more atoms on their respective velocity class, relative to the line center. Thus the UBC laser system sweeps like a comb many atoms from velocity classes that would not be excited with a low power laser and therefore increases the sodium return.

about 1500 photons that should be counted per shot in the counting system. However, coincidence losses have to be taken into account, which result in case two photons arrive within the dead time of the PMT (3 ns) or the discriminator (10 ns for the old counting system, 2 ns for the new system). Our design with 4 PMTs reduces such risk significantly, but nevertheless, with a photon arrival frequency per PMT of $\nu \approx 5$ MHz and $\tau = 2$ ns pulse pair resolution, the coincidence losses are with

$$\eta_{\text{coinc}} = \frac{1}{\tau \nu + 1}, \quad (A.25)$$

less than 1%, hence negligible for this general sodium layer scenario. In case of sporadic sodium layers that might last for hours and have been detected with peak densities 10 times higher than the background, the losses go up to 7% and become an accountable factor. In order to compare the return flux of the UBC lidar with other AO-systems, we use a return flux definition of photons per unit solid angle, columnn density, laser power and second (Holzlöhner et al., 2010). With $3.2 \cdot 10^{13}$ photons emitted per laser shot, in
one second we obtain $1.6 \cdot 10^{15}$ photons. Dividing by $4\pi$ and 5 W average laser power, as well as the column density results in 0.64 ph/sr/s/W/(atoms/m$^2$). This compares to the published return fluxes (see Eqn. A.8) of 258 ph/sr/s/W/(atoms/m$^2$) (Holzlöhner et al., 2010) for a continuous-wave (cw) laser system. The lidar system is optimized for the most return flux per laser shot, while cw systems are optimized for the most return flux per second. This results in a 500 times less effective lidar system if photons per one second laser illumination are counted, but a 10000 times more effective lidar system if photons per 6 ns of laser illumination are counted.

A.6 Summary of Data, Collected from July 9th 2008 until September 1st 2010

On the following pages, tables with a yearly raw data acquisition summary are given for the UBC lidar system. Every night is listed with one entry if the settings stayed the same, otherwise more than one line entry is used for one night. All times are listed in UTC. The counting system changed at the end of July 2009, and with it the stored data format. With the old system only one bin size setting was allowed over the entire range for one shot. With the emphasis on high-resolution Na data, no Rayleigh could be stored for every shot. Instead for each night, the first 5 minutes for a night were spent on low-resolution profiles over the entire atmosphere. With the new counting system, two different setting for bin sizes within one laser shot are possible. This enables us to record the Rayleigh backscatter starting at 45 km with low resolution (600 m bin width, 49 bins) and then with the light being recorded from the 75 km or above region, we switch to high resolution (3.6 m bin width) recording for the sodium layer until the maximum number of bins is reached at 113 km. Table A.3 shows the listing. In summary, in 2008, the UBC lidar system was operational and began routine observations on July 9th with the old counting system. A total of 110 hours were obtained until End October 2008.
Bad weather and telescope-related maintenance prevented us from taking data over the winter. In 2009, observations started again in late June and 56 hours were obtained in July, until the counting system was swapped in Early August 2009. Table A.4 shows the listing for the old counting system. After commissioning of the new counting system, routine data collection started shortly after in August 2009 and 56 hours were obtained until October 8th 2009. Bad weather prevented us from taking data over the winter. 2009 data acquisition summary from the new counting system are listed in Table A.5. Data collection started in 2010 on February 19th and went on every clear night until September 1st 2010. The outcome is listed in table A.5 and contains 194 hours of sodium data as well as 25 hours of Ozone data, for which a detuned laser beam was launched and backscatter recorded from the lower atmosphere to investigate inelastic laser effects such as off-line backscatter contamination due to Raman scattering of various atmospheric molecules, including Ozone.

### Table A.3: Summary of UBC lidar observations for 2008 starting on July 9th 2008 (old counting system).

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Table A.3 to be continued on next page
### Appendix A. Detailed Sodium Layer Lidar Design

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Table A.4: Summary of UBC lidar observations for 2009 until July 31st 2009 (old counting system).

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Appendix B

Absorption Cross Section Derivation using Hyperfine Interaction

Like already described in Section 4.2.2, the interaction (coupling) between the nuclear spin and the total electron angular momentum can be induced by a magnetic field $\vec{B}_{e,0}$, which the optical electron imposes at the location of the nucleus and is described by the magnetic nuclear dipole moment $\vec{\mu}_I$. Hence, the Hamiltonian for this coupling is

$$\mathcal{H}_{\text{Dip}} = -\vec{\mu}_I \cdot \vec{B}_{e,0}$$

the nuclear dipole moment $\vec{\mu}_I$ is $\vec{\mu}_I = g_k \mu_k \frac{\vec{I}}{\hbar} = \mu_I \hbar \left| \frac{\vec{I}}{\hbar} \right|$. The nuclear g-factor $g_k = \frac{\mu_k}{\mu}$ can only be measured and for $^{23}\text{Na}$ it is $-0.00080461080(80)$ (Steck (2009)). $\mu_k = \frac{e \hbar}{2m_P}$ is the nuclear magneton. Thus for the Hamiltonian of the dipole interaction follows, with $\vec{B}_{e,0} = B_{e,0} \frac{\vec{J}}{\hbar |\vec{J}|}$

$$\mathcal{H}_{\text{Dip}} = -\frac{\mu_I \mu_k B_{e,0}}{\hbar^2 |\vec{I}| |\vec{J}|} \vec{I} \cdot \vec{J}$$

The energy expectation value for this Hamiltonian is then the energy shift, with which the fine structure level has to be shifted. The product of both operators $\vec{I} \cdot \vec{J} = \frac{1}{2} (\vec{F}^2 - \vec{I}^2 - \vec{J}^2)$ can be substituted with the sum of the square of the operators that have real Eigenvalues ($\hbar^2 F(F + 1)$, $\hbar^2 I(I + 1)$ and $\hbar^2 J(J + 1)$) and hence that can be used as “good” quantum numbers to calculate the energy shifts:

$$E_{\text{Dip}} = \frac{A}{2} [F(F + 1) - I(I + 1) - J(J + 1)] \quad \text{with} \quad A = -\frac{\mu_I \mu_k B_{e,0}}{\hbar^2 |\vec{I}| |\vec{J}|}$$
Like for all angular momentum couplings, \( F \) can adopt all integer values from \(|I - J| \leq F \leq I + J\), with \( J > I \) and hence, \( 2I + 1 \) possible values for \( F \) are develop. Each term is degenerate \( 2F + 1 \)-time, which will be important when calculating the intensities of every single hyperfine transition contribution.

With nuclear spins, whose quantum number is \( I < 1 \), the magnetic dipole moment is the only moment, which can interact with the total electron angular momentum. However, for nuclear spins with \( I > 1 \) (our case for \( ^{23}\text{Na} \)), also the magnetic quadrupole moment is important. The charge distribution in the nucleus and hence the potential is hereby not anymore radially symmetric. Thus, in this case, the Hamiltonian for electrostatic interaction (Coulomb) for every proton and electron at its specific location is important (\( \mathcal{H}_{el} = -e^2/(4\pi\varepsilon_0 |\vec{r}_e - \vec{r}_p|) \)). If \( |\vec{r}_e| \gg |\vec{r}_p| \), which is usually given at an atom, a multipole expansion in spherical symmetric coordinates (Legendre polynomials and spherical harmonics) is a good approximation. This is carried out in \cite{Wiegand2001} after some time, following quadrupole operator, only dependent on \( I \) and \( J \) is the result:

\[
\mathcal{H}_{\text{Quad}} = -eQ \left( \frac{\partial^2 V_e}{\partial z^2} \right) \frac{3(\hat{T} \cdot \hat{T})^2 + \frac{3}{2}(\hat{T} \cdot \hat{T}) - I(I+1)J(J+1)}{2I(2I-1)J(2J-1)} \tag{B.4}
\]

\( Q \) hereby the expectation value of the state \(|I, M_I = I\rangle\), summed over all protons, in case the direction of \( \hat{T} \) is the principle axis of the quadrupole tensor. The second derivative in Eqn. \( \text{B.4} \) results from the field gradient at the location of the nucleus, induced from the electron jacket. From this Hamiltonian, it follows with perturbation theory of first order the energy shift, with which the hyperfine levels, due to the quadrupole interaction are shifted with respect to the fine structure levels:

\[
E_{\text{Quad}} = \langle IJFM_F | \mathcal{H}_{\text{Quad}} | IJFM_F \rangle = \frac{B}{4} \frac{3C(C+1) - 2I(I+1)J(J+1)}{I(2I-1)J(2J-1)} \tag{B.5}
\]

with \( I \geq 1 \) and \( J \geq 1 \)

\( C \) is hereby the abbreviation \( C = F(F+1) - I(I+1) - J(J+1) \), and \( B = eQ \left( \frac{\partial^2 V_e}{\partial z^2} \right) \). As
already clear from this short derivation, the $B$-factor as well as the $A$-Factor (hyperfine structure constants) of the magnetic dipole have to be calculated quite complicated. With experiments, however, these factors can be derived from hyperfine spectra. They are given in [Steck (2009)] and summarized in Table B.1. For the simulation of the absorption cross section spectrum, the line strength must be determined. This can be done by calculating the expectation value of the dipole operator for two electron states where the wave function subtends opposite parity. Like for the Russell-Saunders coupling, the calculation is identical and the statistical weights (relative line strengths) of the transition can be given with the prime indicating the excited level and $\gamma$ indicating all quantum numbers of the respective state not used for the hyperfine transition under investigation ([Wiegand, 2001] ($J = J' - 1$):

\[
S(\gamma,I,J,F;\gamma',I,J+1,F+1) = \frac{(F-I+J+1)(F-I+J+2)(F+I+J+3)(F+I+J+2)}{4(F+1)}
\]

\[
S(\gamma,I,J,F;\gamma',I,J+1,F) = \frac{(2F+1)(F-I+J+1)(F+I-J)(F+I+J+2)(I-F+J+1)}{4F(F+1)}
\]

\[
S(\gamma,I,J,F;\gamma',I,J+1,F-1) = \frac{(F+I-J-1)(I-F-J)(I+F-J)(I-F+J+1)}{4F}.
\]
Appendix B. Absorption Cross Section Derivation using Hyperfine Interaction  272

After calculating each transition with its frequency shift and intensity, an adequate line profile has to be chosen to approximate the final absorption cross section spectrum. The natural line width is described by a Lorentzian, while the Doppler broadening can be best described using a Gaussian, hence a Voigt profile has been chosen (Eqn. B.7) (Arnold et al., 1969).

\[
E_{\lambda} = E_{\lambda,0} \left\{ \left(1 - \frac{\Delta \lambda_L}{\Delta \lambda_V} \right) e^{-2.772 \left( \frac{\lambda - \lambda_0}{\Delta \lambda_V} \right)^2} + \frac{\Delta \lambda_L}{\Delta \lambda_V} \right\} + 0.016 \left(1 - \frac{\Delta \lambda_L}{\Delta \lambda_V} \right) \frac{\Delta \lambda_L}{\Delta \lambda_V} \left[ e^{-0.4 \left( \frac{\lambda - \lambda_0}{\Delta \lambda_V} \right)^{2.25}} - \frac{10}{10 + \left( \frac{\lambda - \lambda_0}{\Delta \lambda_V} \right)^{2.25}} \right]
\]

(B.7)

\[
E_{\lambda,0} = \frac{1}{\Delta \lambda_V \left[ 1.065 + 0.447 \left( \frac{\Delta \lambda_L}{\Delta \lambda_V} \right) + 0.058 \left( \frac{\Delta \lambda_L}{\Delta \lambda_V} \right)^2 \right]}
\]

(B.8)

and \( \Delta \lambda_L \) is used for the FWHM of the respective profiles, Gaussian, Lorentzian or Voigt. \( \Delta \lambda_V \) is calculated from the Gaussian and Lorentzian width via

\[
\Delta \lambda_V = \frac{\Delta \lambda_L}{2} + \sqrt{\Delta \lambda_L^2 + \Delta \lambda_G^2}.
\]

(B.9)
Appendix C

Log of PTP Observations from December 2009 to August 2010

Table C.1: Summary of data collection with the PTP on Mauna kea, IN and OUT of CFHT dome

<table>
<thead>
<tr>
<th>Date (UT)</th>
<th>Start (UT)</th>
<th>Stop (UT)</th>
<th>Obs. (IN)</th>
<th>Raw [h]</th>
<th>Loc. (OUT)</th>
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<td>Summary</td>
<td>-</td>
<td>-</td>
<td>216</td>
<td>OUT</td>
<td>92</td>
<td></td>
<td>15 m N of weather tower</td>
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<tr>
<td>Summary</td>
<td>-</td>
<td>-</td>
<td>38</td>
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<td>55</td>
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<td>15 m N of weather tower</td>
</tr>
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<td>2009/12/1</td>
<td>4:8</td>
<td>8:4</td>
<td>3.93</td>
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<td></td>
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<tr>
<td>2009/12/1</td>
<td>8:6</td>
<td>12:16</td>
<td>4.16</td>
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<td></td>
</tr>
<tr>
<td>2009/12/1</td>
<td>12:20</td>
<td>14:18</td>
<td>1.96</td>
<td>OUT</td>
<td>15 m N of weather tower</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009/12/2</td>
<td>6:44</td>
<td>7:24</td>
<td>0.66</td>
<td>IN</td>
<td>78</td>
<td>Mezz/STW W / facing E through dome</td>
<td></td>
</tr>
<tr>
<td>2009/12/2</td>
<td>7:31</td>
<td>8:29</td>
<td>0.96</td>
<td>IN</td>
<td>-</td>
<td>Mezz/STW W / facing E through dome</td>
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</tr>
<tr>
<td>2009/12/2</td>
<td>8:54</td>
<td>9:26</td>
<td>0.53</td>
<td>IN</td>
<td>-</td>
<td>TelFl W / facing E move after 15 minutes</td>
<td></td>
</tr>
<tr>
<td>2009/12/2</td>
<td>9:43</td>
<td>11:43</td>
<td>2.0</td>
<td>IN</td>
<td>-</td>
<td>TelFl SE / facing straight up near dome DIMM, 3 times move</td>
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Table C.1 to be continued on next page
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<td>1.2</td>
<td>IN</td>
<td>-</td>
<td></td>
<td>MovSTW E / facing W over telescope, 2 times move</td>
</tr>
<tr>
<td>2009/12/2</td>
<td>13:48</td>
<td>15:16</td>
<td>1.46</td>
<td>IN</td>
<td>-</td>
<td></td>
<td>W of South Pier / facing W, South of telescope</td>
</tr>
<tr>
<td>2009/12/3</td>
<td>7:37</td>
<td>9:21</td>
<td>1.73</td>
<td>IN</td>
<td>73</td>
<td></td>
<td>Mezz/STW W / facing E through dome, 2 times move</td>
</tr>
<tr>
<td>2009/12/3</td>
<td>9:41</td>
<td>10:39</td>
<td>0.96</td>
<td>IN</td>
<td>-</td>
<td></td>
<td>TelFl W / facing E move after 15 minutes</td>
</tr>
<tr>
<td>2009/12/3</td>
<td>13:42</td>
<td>15:56</td>
<td>2.23</td>
<td>IN</td>
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<td>9:9</td>
<td>1.23</td>
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<td></td>
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<tr>
<td>2009/12/8</td>
<td>12:40</td>
<td>15:58</td>
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<td>2009/12/9</td>
<td>11:45</td>
<td>15:45</td>
<td>4.0</td>
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<td>11:13</td>
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<td>IN</td>
<td>-</td>
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<tr>
<td>2010/3/3</td>
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<td>14:47</td>
<td>0.06</td>
<td>IN</td>
<td>-</td>
<td></td>
<td>TelFl E of S Pier</td>
</tr>
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<td>2010/3/3</td>
<td>14:32</td>
<td>14:46</td>
<td>0.23</td>
<td>IN</td>
<td>-</td>
<td></td>
<td>no moon in FoV</td>
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## Table C.1 – continued from previous page –

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<td>26 TelFl near STW W / 3 times move</td>
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</tr>
<tr>
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<td></td>
</tr>
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<td>2.56</td>
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<td></td>
</tr>
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<td>2010/5/23</td>
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<td>7:32</td>
<td>0.8</td>
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</tr>
<tr>
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<td>11:46</td>
<td>4.0</td>
<td>OUT</td>
<td>- S of weather tower – minor tracking issues – solved</td>
<td></td>
</tr>
<tr>
<td>2010/5/23</td>
<td>11:46</td>
<td>12:8</td>
<td>0.36</td>
<td>OUT</td>
<td>- S of weather tower</td>
<td></td>
</tr>
<tr>
<td>2010/5/24</td>
<td>6:6</td>
<td>10:6</td>
<td>4.0</td>
<td>OUT</td>
<td>89 S of weather tower / minor tracking issues, re-centering</td>
<td></td>
</tr>
<tr>
<td>2010/5/24</td>
<td>10:7</td>
<td>12:51</td>
<td>2.73</td>
<td>OUT</td>
<td>- S of weather tower</td>
<td></td>
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<tr>
<td>2010/5/25</td>
<td>6:12</td>
<td>7:38</td>
<td>1.43</td>
<td>OUT</td>
<td>87 S of weather tower / baffle blocked some light to diodes 1 and 8</td>
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<td>0.1</td>
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<td>- S of weather tower / baffle blocked some light to diodes 1 and 8</td>
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<tr>
<td>2010/5/25</td>
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<td>12:0</td>
<td>4.0</td>
<td>OUT</td>
<td>- S of weather tower</td>
<td></td>
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<tr>
<td>2010/5/25</td>
<td>12:0</td>
<td>13:30</td>
<td>1.5</td>
<td>OUT</td>
<td>- S of weather tower</td>
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<tr>
<td>2010/5/26</td>
<td>6:10</td>
<td>9:4</td>
<td>2.9</td>
<td>OUT</td>
<td>77 SE of weather tower</td>
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<tr>
<td>2010/5/26</td>
<td>9:49</td>
<td>13:49</td>
<td>4.0</td>
<td>OUT</td>
<td>- SE of weather tower</td>
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Table C.1 to be continued on next page
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<td>OUT</td>
<td>-</td>
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<td>SE of weather tower</td>
</tr>
<tr>
<td>2010/5/27</td>
<td>5:2</td>
<td>9:2</td>
<td>4.0</td>
<td>OUT</td>
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<td>SE of weather tower</td>
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<td>12:46</td>
<td>3.73</td>
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<td>SE of weather tower</td>
</tr>
<tr>
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<td>14:44</td>
<td>3.53</td>
<td>OUT</td>
<td>25</td>
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<td>NNE from weather tower / diode 1 missalignment</td>
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<tr>
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<td>14:45</td>
<td>3.06</td>
<td>OUT</td>
<td>96</td>
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<td>S of weather tower</td>
</tr>
<tr>
<td>2010/6/3</td>
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<td>14:58</td>
<td>3.26</td>
<td>OUT</td>
<td>99</td>
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</tr>
<tr>
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<td>14:44</td>
<td>3.53</td>
<td>OUT</td>
<td>98</td>
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<td>S of weather tower</td>
</tr>
<tr>
<td>2010/6/23</td>
<td>8:19</td>
<td>9:11</td>
<td>0.86</td>
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<td>73</td>
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</tr>
<tr>
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<td>-</td>
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<tr>
<td>2010/6/23</td>
<td>11:7</td>
<td>11:12</td>
<td>0.08</td>
<td>IN</td>
<td>-</td>
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<td>14:42</td>
<td>2.58</td>
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<td>-</td>
<td></td>
<td>S of weather tower / partial lunar eclipse</td>
</tr>
<tr>
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<td>14:37</td>
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<td>94</td>
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<td>14:13</td>
<td>0.22</td>
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<td>-</td>
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<td>N of weather tower / diode 6</td>
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<td>2010/7/1</td>
<td>9:42</td>
<td>13:42</td>
<td>4.0</td>
<td>OUT</td>
<td>93</td>
<td></td>
<td>lost ground connection - negative voltages</td>
</tr>
<tr>
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<td>13:42</td>
<td>15:8</td>
<td>1.41</td>
<td>OUT</td>
<td>-</td>
<td></td>
<td>N of weather tower / diode 6</td>
</tr>
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<td>OUT</td>
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<td>E of weather tower / diode 6</td>
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<td>2010/7/2</td>
<td>13:34</td>
<td>14:49</td>
<td>1.25</td>
<td>OUT</td>
<td>-</td>
<td></td>
<td>E of weather tower / diode 6</td>
</tr>
<tr>
<td>2010/7/3</td>
<td>9:58</td>
<td>13:58</td>
<td>4.0</td>
<td>OUT</td>
<td>96</td>
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<td>0.88</td>
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<td>NE of weather tower / diode 6 lost ground connection - negative voltages</td>
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<tr>
<td>2010/7/4</td>
<td>10:28</td>
<td>14:28</td>
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<td>OUT</td>
<td>96</td>
<td>NE of weather tower / diode 6 lost ground connection - negative voltages</td>
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<td>14:52</td>
<td>0.38</td>
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<td>NE of weather tower / diode 6 lost ground connection - negative voltages</td>
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<tr>
<td>2010/7/19</td>
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Table C.1 to be continued on next page
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<td>14:28</td>
<td>0.23</td>
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Appendix D

Results for Individual Nights of PTP Observations

In this chapter, results from a few nights of data from the PTP are presented. These plots are quite detailed, and in this paragraph each panel is described. For each night, two separate plots are shown. Each page starts with the $C_N^2$-profile map for the night. The ordinate is the zenith-corrected height on a logarithmic scale, and the abscissae represents the observation time. Whenever height is mentioned in the following, the vertical height above the instrument is meant. Often there are gaps. These result from either data acquisition stops or bad data that have been removed. The color code in the $C_N^2$-maps represents the logarithm of the structure constant and ranges from -13 (very strong optical turbulence) to -19 (very weak optical turbulence). The next two panels show the derived seeing value time series (FWHM in arcsec for $\lambda = 500\text{nm}$). ONLY the ground layer (GL) seeing with NO free atmosphere contribution is displayed. In the first of the two seeing time series panels, the GL seeing ABOVE the indicated height (seen in the legend on the right side) is shown. To indicate, from which part of the atmosphere the most contribution to the total seeing comes from, 5 individual ranges are shown. The upper end of the ground layer is set to 1000 m, but the influence from the range between 500 m and 1 km on the GL seeing is minimal. The same holds for the GL seeing panel underneath, however this time it indicates the GL seeing BELOW the indicated height.

Two panels with cumulative distribution functions for the seeing time series follow after the turbulence map. One is for the “ABOVE”-data, and one is for the “BELOW”-case. In the ABOVE case, two additional lines are drawn. They represent the total seeing
from the MKAM DIMM instrument, as well as from the CFHT Dome DIMM instrument. As no free atmosphere seeing is added to the PTP data, a comparison between the DIMMs and the PTP is not possible. However, these data give a hint as to how much seeing the free atmosphere contributes. The difference between dome DIMM and MKAM DIMM likely indicates influences from the CFHT dome, hence local turbulent effects.

In the last plot, wind speed (color coded), wind direction (in a $\pm 20^\circ$-band), dome azimuth and moon azimuth are shown. Wind information is only shown if the wind speed is above 1.5 m/s, as otherwise wind direction is uncertain. This is a helpful plot for the data taken from inside, to see how the dome was located with respect to the moon and the wind. But also for the outside data, it is very useful to see from what direction and how strong the wind was blowing.

On the second page, the $C_N^2$ profile map is shown again for reference. In the next plot, MKAM DIMM, CFHT dome DIMM, and the PTP seeing above 6 m time series are plotted.

The following panel shows GL seeing vs. height. It indicates the GL seeing that would be seen by telescope observing a star at the zenith from the indicated height. In these plots a strong rise in seeing below 30 m or 40 m can be seen. This shows the ground layer. If several nights from different outside data series are compared, it becomes obvious that wind direction plays a crucial role in this plot.

The last two panels indicate meteorological data time series, such as temperature, relative humidity and pressure.
Appendix D. Results for Individual Nights of PTP Observations

D.1 Inside Data

2009-12-02 INSIDE
Appendix D. Results for Individual Nights of PTP Observations

Timevariations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea INSIDE CFHT dome on 2009-12-02.

Seating (FWHM) comparison between MKAM DIMM and PTP GL > 9m -- 2009-12-02.

Median GL seating vs height -- 2009-12-02.


Relative humidity [%] and pressure [mba] on Mauna Kea for 2009-12-02.
Appendix D. Results for Individual Nights of PTP Observations

2009-12-03 INSIDE
Appendix D. Results for Individual Nights of PTP Observations

Time variations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea INSIDE CFHT dome on 2009-12-03.

Seeing (FWHM) comparison between MKAM DIMM and PTP GL > 6m – 2009-12-03.

Median GL seeing vs height – 2009-12-03.

Temperature [deg C] on Mauna Kea for 2009-12-03.

Relative humidity [%] and pressure [mbar] on Mauna Kea for 2009-12-03.
Appendix D. Results for Individual Nights of PTP Observations

2010-07-23 INSIDE
Appendix D. Results for Individual Nights of PTP Observations

![Graphs showing time variations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea INSIDE CFHT dome on 2010-07-23.](image)

![Graph showing seeing (FWHM) comparison between MKAM D/mm and PTP GL > 6 m - 2010-07-23.](image)

![Graph showing median GL seeing vs height - 2010-07-23.](image)

![Graph showing temperature [deg C] on Mauna Kea for 2010-07-23.](image)

![Graph showing relative humidity [%] and pressure [mbar] on Mauna Kea for 2010-07-23.](image)
Appendix D. Results for Individual Nights of PTP Observations

2010-08-19 INSIDE

Time variations of $\text{C}_{\text{m}}^2$ profiles for the Ground Layer (GL) on Mauna Kea INSIDE CFHT dome on 2010-08-19.

GL Seeing (FWHM) in arcsec ABOVE indicated height

GL Seeing (FWHM) in arcsec BELOW indicated height

Cumulative Distribution for Seeing ABOVE indicated height

Cumulative Distribution for Seeing BELOW indicated height

Wind direction band (±20 deg). Color-coded Wind Speed [m/s] and Azimuthal Position of PTP and dome.
Appendix D. Results for Individual Nights of PTP Observations

2010-08-20 INSIDE
Appendix D. Results for Individual Nights of PTP Observations

Time variations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea INSIDE CFHT dome on 2010-08-20

Seeing (FWHM) comparison between MKAM DIAM and PTP GL > 6m – 2010-08-20

Median GL seeing vs height – 2010-08-20

Temperature [deg C] on Mauna Kea for 2010-08-20

Relative humidity [%] and pressure [mbar] on Mauna Kea for 2010-08-20
D.2 Outside Data

2009-12-01 OUTSIDE
Appendix D. Results for Individual Nights of PTP Observations

Time variations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea OUTSIDE CFHT dome on 2009-12-010

Seeing (FWHM) comparison between MKAM DIMM and PTP GL > 6m -- 2009-12-010

Median GL seeing vs height -- 2009-12-010

Temperature [deg C] on Mauna Kea for 2009-12-010

Relative humidity [%] and pressure [mb] on Mauna Kea for 2009-12-010
Appendix D. Results for Individual Nights of PTP Observations

2009-12-09 OUTSIDE

[Graphs and images showing time variations and statistical distributions of various meteorological parameters on Mauna Kea OUTSIDE CFHT dome on 2009-12-09, including seeing, wind direction, and speed.]
Appendix D. Results for Individual Nights of PTP Observations

2010-05-27 OUTSIDE

Time variations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea OUTSIDE CFHT dome on 2010-05-27.
Appendix D. Results for Individual Nights of PTP Observations

Time variations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea OUTSIDE CFHT dome on 2010-05-27T.

Seeing (FWHM) comparison between MKAM D1MM and PTP GL > 6m -- 2010-05-27T.

Median GL seeing vs height -- 2010-05-27T.

Temperature [deg C] on Mauna Kea for 2010-05-27T.

Relative humidity [%] and pressure [mb] on Mauna Kea for 2010-05-27T.

Pressure [mb] and Relative Humidity [%] on Mauna Kea for 2010-05-27T.
Appendix D. Results for Individual Nights of PTP Observations

2010-07-30 OUTSIDE
Appendix D. Results for Individual Nights of PTP Observations

![Graphs showing time variations of $C_N^2$ profiles for the Ground Layer (GL) on Mauna Kea OUTSIDE CFHT dome on 2010-07-300.](image)

![Graph showing seeing (FWHM) comparison between MKAM DIMM and PTP GL > 6 m -- 2010-07-300.](image)

![Graph showing median GL seeing vs height -- 2010-07-300.](image)

![Graph showing temperature [degC] on Mauna Kea for 2010-07-300.](image)

![Graph showing relative humidity [%] and pressure [mbar] on Mauna Kea for 2010-07-300.](image)
Appendix D. Results for Individual Nights of PTP Observations

2010-08-02 OUTSIDE

Time variations of $C_n^2$ profiles for the Ground Layer (GL) on Mauna Kea OUTSIDE CFHT dome on 2010-08-02.

GL Seeing (FWHM) in arcsec ABOVE indicated height:

- 1m
- 6m
- 20m
- 50m
- 100m

GL Seeing (FWHM) in arcsec BELOW indicated height:

- 6m
- 20m
- 50m
- 100m
- 1km

Cumulative distribution for GL seeing ABOVE indicated height:

- 1m (0.42)
- 6m (0.38)
- 20m (0.28)
- 50m (0.22)
- MKAM DIMM (0.44)
- Dome DIMMM (0.69)

Wind direction band (+20 deg), color-coded Wind Speed [m/s] and Azimuthal Position of PTP and dome.

Wind Speed (m/s):

- 0
- 6
- 12
- 18
- 24
- 30

UT time [h]
Appendix D. Results for Individual Nights of PTP Observations

Time variations of $C_v^2$ profiles for the Ground Layer (GL) on Mauna Kea OUTSIDE CFHT dome on 2010-08-02O

Seeing (FWHM) comparison between MKAM DIMM and PTP GL > 9m -- 2010-08-02O

Median GL seeing vs height -- 2010-08-02O

Temperature [deg C] on Mauna Kea for 2010-08-02O

Relative humidity [%] and pressure [mbar] on Mauna Kea for 2010-08-02O
Appendix D. Results for Individual Nights of PTP Observations

2010-08-23 OUTSIDE

Time variations of $c_n^2$ profiles for the Ground Layer (GL) on Mauna Kea OUTSIDE CFHT dome on 2010-08-23.

GL Seeing (FWHM) in arcsec ABOVE indicated height:
- 1m
- 6m
- 20m
- 50m
- 100m

GL Seeing (FWHM) in arcsec BELOW indicated height:
- 6m
- 20m
- 50m
- 100m
- 1km

Cumul Distr. for GL seeing ABOVE indicated height:
- 1m (0.48°)
- 6m (0.44°)
- 20m (0.31°)
- 50m (0.17°)
- 100m (0.12°)
- MKAM DIMM (0.46°)
- Dome DIMM (0.61°)

Wind direction band (+20 deg), color-coded Wind Speed [m/s] and Azimuthal Position of PTP and dome.

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