Studies of atmospheric properties for optical ground-based astronomy and methods to enhance laser guide star adaptive optics performance

by

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Abstract

Ground-based astronomy suffers from waveform distortion produced by the turbulent atmosphere, which prevents telescopes from reaching diffraction-limited resolution. Modern large telescopes and next generation extremely-large telescopes use or will use adaptive optics systems with laser guide stars to correct for atmospheric wavefront distortion. The first part of the thesis deals with astronomical site testing and the second part with methods for adaptive optics system improvement.

Meteorological data for 15 observatory sites were studied. Monthly averages of cloud cover, wind speed at 200 hPa, precipitable water vapour, vertical wind velocity and aerosol index were compared for the sites. The long-term evolution over 45 years of the five atmospheric quantities was investigated.

Site testing campaigns characterize potential telescope sites in terms of optical turbulence. Using scintillometers, ground layer turbulence profiles can be measured. For an assessment of sites long-term statistics are needed. Two campaigns for daytime and nighttime turbulence profiling have been started and preliminary results are described.

Methods for increasing adaptive optics system performance are studied. Polarization modulation of the adaptive optics laser might be an useful method. Experimental results are presented. The method also enables measurements of the Larmor frequency and the magnetic field strength in the mesosphere. The average Larmor frequency is 260.4 kHz. We found a maximum LGS return flux enhancement of 18% for a pulsed amplitude modulation at Larmor frequency compared to amplitude modulation offset from the Larmor frequency. For polarization modulation at the Larmor frequency a 6% increase in LGS return flux was found over polarization modulation offset by 30-kHz from the Larmor frequency.

Adaptive optics system could also benefit from an estimate of the mesospheric sodium density
Abstract

profile. Such profiles can be retrieved by partial amplitude modulation, with pseudo-random binary sequences, of continuous-wave lasers. Results for an experiment at the Large Zenith Telescope in Maple Ridge, and a feasibility study of this method for extremely-large telescopes, are presented. The method could be used on extremely-large telescopes to estimate the sodium density profile with a temporal resolution of a few seconds.
Lay summary

Optical turbulence induced by the atmosphere degrades image quality of observations in astronomy. Large optical telescopes use or will use adaptive optics systems to mitigate the effects of turbulence.

In this thesis observing conditions at different telescope sites and methods for increasing adaptive optics systems performance are studied. Meteorological data for 15 sites over a period of 45 years has been studied. The start and preparation of two on-site testing campaigns, one for daytime turbulence and one for nighttime turbulence, are described. In addition, two techniques for increasing laser guide star adaptive optics performance were studied. For the first technique, called polarization modulation, the increase in laser guide star brightness was studied. The second technique, called continuous wave lidar method, aims at obtaining vertical sodium density profiles.
Preface

Chapter 3 is a manuscript co-authored with P. Hickson, R. Yang and M. Sarazin. J. Hellemeier is the primary author. Data processing and data analysis were primarily done by R. Yang and J. Hellemeier. The statistical analysis and manuscript preparation were performed by P. Hickson and J. Hellemeier, with comments and revisions provided by all contributors. P. Hickson and M. Sarazin supervised the project.

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Acronyms

**ALMA**  Atacama Large Millimeter Array.

**AO**  adaptive optics.

**AOM**  acousto-optic modulator.

**APD**  avalanche photo-diode.

**ATP**  Arctic Turbulence Profiler.

**CHIME**  Canadian Hydrogen Intensity Mapping Experiment.

**CME**  coronal mass ejection.

**CMOS**  complementary metal-oxide-semiconductor.

**CTA**  Cherenkov Telescope Array.

**CW**  continuous-wave.

**DIMM**  differential image motion monitor.

**DM**  deformable mirror.

**ELT**  European Extremely Large Telescope.

**ELTs**  extremely-large telescopes.

**EOM**  electro-optic modulator.

**ESO WLGSU**  European Southern Observatory Wendelstein Laser Guide Star Unit.

**FET**  field-effect transistor.
**Acronyms**

**FWHM** full-width-at-half-maximum.

**GLAO** ground-layer adaptive optics.

**GMT** Giant Meter Telescope.

**hcc** high-level cloud cover.

**ING** Isaac Newton Group of Telescopes.

**JWST** James Webb Space Telescopes.

**lcc** low-level cloud cover.

**LGS** laser guide star.

**LIA** lock-in amplifier.

**LZT** Large Zenith Telescope.

**MASS** multi-aperture scintillation sensor.

**mcc** mid-level cloud cover.

**MOF** magneto-optical filter.

**NGS** natural guide star.

**ORM** Observatory Roque de la Muchachos.

**PMT** photomultiplier tube.

**PRBS** pseudo-random binary sequences.

**PSF** point spread function.

**PTP** Portable Turbulence Profiler.

**PWV** precipitable water vapour.
Acronyms

**SAMM** solar activity MOF monitor.

**SCIDAR** scintillation detection and ranging.

**SHG** second-harmonic generation.

**SLODAR** slope detection and ranging.

**SNR** signal-to-noise ratio.

**SODAR** sound detection and ranging.

**TDC** time-to-digital converter.

**TMT** Thirty Meter Telescope.

**TTL** transistor-transistor logic.

**UV** ultraviolet.

**WHT** William Herschel Telescope.

**WMM2105** World Magnetic Model.

**WMW** Wilcoxon-Mann-Whitney.
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Chapter 1

Introduction to atmospheric wavefront distortion

The light collected by ground-based telescopes has propagated through the turbulent Earth atmosphere prior to arrival at the Earth’s surface. Because of this, initially parallel light waves are distorted, leading to blurred images. Originally, Isaac Newton anticipated the unwanted image degradation by the atmosphere. In his book “Opticks”, he foresaw mountain tops beneath a layer of still air as an ideal site for (optical) telescopes. Light waves propagating through the atmosphere experience index of refraction variations arising from fluctuations of temperature, density and air pressure. The image of a point-like source appears blurred, and is referred to as a seeing disc. Seeing in astronomy determines the resolution in an image and is a combination of blurring and image motion. In addition, the light received shows intensity fluctuations, so called scintillation. The energy of a light wave travels perpendicular to its wavefront. Scintillation effects thus arise from bending of the wave front by index of refraction variations.

Light from a distant point-like source entering an aperture, will form a diffraction pattern in the image plane, called the point-spread function (PSF). The diffraction pattern in the image or focal plane can be described by Fraunhofer diffraction theory. Undistorted parallel wavefronts from a distant point-like source entering a circular, unobstructed aperture, will form the diffraction pattern of an Airy disk. The intensity distribution in the image plane is given by,

\[ I(\theta) = 4I_0 \left( \frac{J_1(ka \sin \theta)}{ka \sin \theta} \right)^2, \]  

where \( J_1 \) is the first order Bessel function, \( k \) is the wavenumber, \( a \) the radius of the aperture and \( \theta \) is the angle between the line from the aperture centre to the point of observation and the line from the aperture centre to the centre of the image plane (optical axis). The Airy disk is the intensity distribution of a circular aperture when the far field approximation is
valid, e.g. when the distance between image plane and aperture is greater than $a^2/\lambda$. The full-width-at-half-maximum (FWHM) for the PSF of a point-like source, is given by

$$\epsilon = 1.029 \frac{\lambda}{D},$$

where $\lambda$ is the wavelength of the light and $D$ is the aperture diameter. Smaller FWHM of the PSF yield increased resolution for astronomical observations. The resolution increases with decreasing wavelength and the resolution increases with increasing aperture size, if the diffraction limit is reached.

Increasing the aperture size of a ground-based telescope automatically increases the sensitivity, as more photons are collected. If no adaptive optics (AO) system is used, the resolution of the telescope does not automatically increase and the resolution is determined by the characteristic length scale of the atmosphere. For a telescope residing below a turbulent atmosphere, the shape of the PSF is determined by the turbulent atmosphere. The image becomes a superposition of many PSFs having slightly fluctuating angles of incidence. For short-exposure images, these multiple PSFs interfere creating speckles in the image. Long-exposure images integrate over many speckles in the centre of the image. Due to the central limit theorem, the intensity distribution in the centre will approach a Gaussian distribution. At the sides of the image the central limit theorem does not hold anymore, yielding a non-uniform intensity distribution. The optimal functions for fitting seeing-limited PSFs will be discussed in Section 2.3.2. Index of refraction variations arise from small scale statistical fluctuations of temperature, density and pressure. When coherent light passes through turbulent cells of the atmosphere, it is distorted and arrives out of phase. This can be seen in Figure 1.1. The fluctuations of the refractive index in the atmosphere can be described by the structure function

$$D_n(r) = \left\langle \left[ n(x + r) - n(x) \right]^2 \right\rangle.$$

The structure function is the ensemble average of the mean square difference of the refractive index for two points separated by a vector $r$.

Space-based telescopes overcome the problem of atmospheric distortion and are able to operate at the diffraction limit. However, space-based telescopes have several disadvantages. They are more expensive than comparable ground-based telescopes and it is difficult to carry out
maintenance or update instruments. The technologies on-board space missions need to be well-established and very robust to minimize possibilities for failure. Nonetheless, space-based telescopes such as the Hubble Space Telescope have made numerous discoveries, contributing a great share to modern astronomy. The entire wavelength spectrum can be observed from space. For ground-based telescopes, the atmosphere (mainly absorption by water vapour in the atmosphere) blocks parts of the spectrum. In astronomy today it is important to use synergies between space-based and ground-based telescopes. For example, space-based telescopes can complement observations of ground-based telescopes by accessing wavelength ranges not accessible from Earth.

At this time large optical telescopes, and in the future next-generation extremely large optical telescopes (ELTs\textsuperscript{1}) complement radio telescopes like the Atacama Large Millimeter Array (ALMA) or the Canadian Hydrogen Intensity Mapping Experiment (CHIME), as well as space-

\textsuperscript{1}Throughout the thesis, the acronym ELTs will be used for extremely-large telescopes in general and the acronym ELT will be used for the European Extremely Large Telescope.
based telescopes like the aforementioned Hubble Space Telescope and the future James Webb Space Telescope (JWST), and also, gamma-ray detectors like the Cherenkov Telescope Array (CTA). These facilities provide means for observations of almost the entire electromagnetic spectrum targeting key questions in astronomy. In recent years gravitational wave detection has become another successful technique for the observation of compact objects (Abbott et al. 2016). Key questions in astronomy address topics from our Solar system to cosmology and reach back to the early Universe. Next-generation extremely large telescopes, like the Thirty Meter Telescope (TMT), the European Extremely Large Telescope (ELT) or the Giant Magellan Telescope (GMT) will play an important role in answering some of these questions. They will benefit from AO systems, already in use on some of the state-of-the-art optical telescopes. AO systems, which will be described later, mitigate the blurring effect of the atmosphere. Telescopes equipped with them, can operate almost at the diffraction limit and reach unprecedented resolution and sensitivity. With these telescopes, researchers are able to look deeper into space and observe at higher redshifts. Future instruments will achieve increased contrasts in photometry and higher resolution in spectroscopy.

The nature of dark matter and dark energy is still not understood. The composition of the Universe and dark matter distribution remain open questions. Massive galaxy halos should be associated with numerous sub-halos. Observations show a discrepancy between observed mass-functions and simulated mass-functions (Klypin et al. 1999; Springel et al. 2008). Future extremely-large telescopes will likely increase the number of observable sub-halos. In the case of the formation and evolution of first galaxies, there is the need for observations of objects at \( z > 10 \), which most-likely would yield a more profound understanding of galaxies. For observations of the kinematics and chemical composition of stars and the inter-stellar medium in galaxies, state-of-the-art facilities are limited to a redshift of \( z \approx 5 \). The formation of galaxies is believed to be strongly linked to black hole formation. A strong correlation between black hole masses and the velocity distribution of the bulge has already been found (Ferrarese & Merritt 2000). ELTs operating with AO systems will facilitate observations of black holes ten times less-massive then at present. Black holes at distances twenty times farther can be observed. As a result the number of galaxies, where the mass of the black hole can be directly measured, will increase by a factor of 1000 (Skidmore et al. 2015). Star formation is another in-depth topic studied. The peak of star formation arising around \( z \approx 2 \) is still not fully understood (Madau & Dickinson 2014). Metal-free star formation, the formation of the first stars, has not been observed so far, since it is believed to occur at redshifts beyond \( z = 10 \) (Greif & Bromm 2004).
Wide-field imaging with ELTs will be able to detect supernovae up to redshifts of $z = 10$. The number of supernovae at a certain redshift will yield an interpolation of the number of earlier-formed stars. Observational data hint at the initial mass function being affected by the chemical composition of the environment over time. However, in general, the sub-stellar region, planet formation in the proto-planetary disk, is not well understood. Regions of young star formation are located around 150 pc away for low-mass star formation and 500 pc (e.g. Orion) for high-mass star formation. Older star formation can be observed in TW Hydrae at 50 pc. The past two decades have revealed an astonishing population of exoplanets (Wright et al. 2011). Characterizing their atmosphere and composition, and unveiling habitable zones around stars still remain tasks open for the future. High-resolution spectrographs of 8-10 m class telescope suffer from too few photons for spectral analysis of the atmosphere of the planet during transits. By the increase in aperture size, ELTs will yield sufficient photons for the spectral analysis by high-resolution spectrographs. In addition, diffraction-limited high-resolution imaging of ELTs in the mid-infrared and near-infrared should spatially resolve the proto-planetary disk. Planet formation should become evident by gaps in the disks. These observations will complement observations by ALMA at radio wavelengths.

The full potential of ELTs can only be reached if these are operated with instruments using AO systems. Improvements of AO systems will lead to higher performance of the telescopes. There is a need for improved understanding of optical turbulence and further development of AO systems, which is one of the motivations for the research presented in this thesis. There is a two-fold focus to this thesis. Firstly, results for site testing of prospective and operative astronomical sites, in terms of weather and optical turbulence, are presented. In addition, techniques for a more-efficient use of laser guide stars (LGS) in AO systems are explored. Chapter 2 gives an introduction to optical turbulence and AO systems. Chapter 3 presents a comparison of weather data for 15 astronomical sites over 45 years. This chapter was originally published as a paper in the 'Monthly Notices of the Royal Astronomical Society'. Chapter 4 presents site testing instruments for optical turbulence and gives a detailed introduction to one of them - the lunar scintillometer. We are using scintillometers for daytime and nighttime turbulence profiling on sites in China and Colombia. First results of the two projects are presented. In Chapter 5 - Chapter 8 the focus shifts to the LGS. In Chapter 5 the theoretical background of atomic physics for sodium LGS excitation is introduced. In Chapter 6 & 7 results from two missions of an experiment using polarization modulation for enhancing LGS return flux and measurements of the Earth’s magnetic field in the mesosphere are shown. Chapter
Chapter 1. Introduction to atmospheric wavefront distortion

[8] deals with a technique for amplitude modulation of a continuous-wave (CW) laser, in order to obtain sodium density profiles from the LGS. Results from an experiment at the Large Zenith Telescope (LZT) in Maple Ridge and numerical results for a performance estimate of the technique for extremely-large telescopes are shown. The thesis concludes with a summary of conclusions and a discussion of future work.
Chapter 2

Atmospheric turbulence and adaptive optics

2.1 Index of refraction variations

The index of refraction determines the speed of light in a medium. If there is a gradient of the refractive index, the velocity of the propagating light changes. The refractive index is dependent on temperature and density, which are linked to pressure through the laws of thermodynamics. In turbulent cells in the atmosphere, temperature and density fluctuate, generating variations in the refractive index. The optical path length through turbulent cells vary, causing phase shifts after the propagation of the electromagnetic wave through the cell. Another effect of the refractive-index fluctuation is the directional bending caused by the bending of light waves. Small random changes in the direction occurring numerous times lead to scintillation; the higher the altitude, the stronger the effect on the ground, since the spatial distances increase. The fluctuation of the refractive index are of random nature and have time scales of milliseconds. Exposure times for observations are normally not shorter than tenths of seconds. The index of refraction in air is given by (Owens 1967)

\[ n(\lambda_0) = 1 + \frac{0.05792105}{238.0185 - (1000/\lambda_0)^2} + \frac{0.00167917}{57.362 - (1000/\lambda_0)^2}, \]  

(2.1)

where \( \lambda_0 \) is the wavelength in vacuum. The index of refraction is related to temperature and pressure by (Birch & Downs 1993)

\[ n(\lambda_0, p, T) - 1 = \frac{p \cdot [n(\lambda_0) - 1]}{96095.43} \cdot \frac{1 + 10^{-8} \cdot [0.601 - 0.00972 \cdot (T - 273.15)] \cdot p}{1 + 0.003661 \cdot (T - 273.15)}, \]  

(2.2)

where \( T \) is temperature in Kelvin and \( p \) is pressure in Pascal. Since pressure fluctuations travel at the speed of sound and are equalized quickly compared to atmospheric timescales,
pressure can be assumed to be uniformly distributed. Refractive index fluctuations depend only on temperature variations. The phase shift for an electromagnetic wave with wavenumber \( k \) reaching an telescope aperture along the line of sight can be calculated by

\[
\delta \phi = k \int_0^\infty [n(z) - \bar{n}] \, dz ,
\]

where the term in the brackets is the difference of the index of refraction from the mean index of refraction \( \bar{n} \) for all rays reaching the aperture. The phase fluctuations are approximately gaussian and have zero mean (Ageorges & Dainty 2000).

### 2.2 Kolmogorov turbulence and the structure constant

In a viscous fluid, such as the atmosphere can be considered to be, there are two types of flow, laminar and turbulent. Laminar flow is characterized by a uniform or homogeneous velocity flow where mixing of layers does not take place. Turbulent flow results in mixing and causes random or stochastic fluctuations in the flow. The transition between laminar and turbulent flow occurs at the critical Reynolds number, and if this number is exceeded turbulent flow will set in. Near the surface, the Reynolds number can be around \( 10^5 \) resulting in strong turbulence, while it decreases for upper layers of the atmosphere. The Navier-Stokes equations are non-linear equations describing viscous flow, in principle the framework for describing turbulence. However, since there is strong non-linearity of the equations, calculating solutions using the Navier-Stokes equations is difficult. It is still not clear, if a smooth set of solutions for the equations does exist for most conditions (Fefferman 2006).

Kolmogorov chose a different approach for describing turbulence. His theory is based on statistical properties, using dimensional analysis (Kolmogorov 1941). Kolmogorov introduced the idea to treat the turbulent flow as a field with statistical properties. Quantities of the random field have global mean values. Even though turbulence patterns and with it the properties of the field may change over large distances, the field can be assumed to be locally homogeneous. In a locally homogeneous field, which in addition is isotropic, the structure function, since it is an ensemble average, no longer depends on position, just on the squared modulus of the separation of any two positions. The covariance function \( B_u(r) \) describes the fluctuations of a quantity \( u \) in a statistical field. It is given by
2.2. Kolmogorov turbulence and the structure constant

\[ B_u(r) = \langle u(x + r)u(x) \rangle. \]  \hspace{1cm} (2.4)

The structure function can be calculated from the covariance by

\[ D_u(r) = \left\langle [u(x + r) - u(x)]^2 \right\rangle = \langle u(x + r)u(x + r) + u(x)u(x) - 2u(x + r)u(x) \rangle \]
\[ = 2(B_u(0) - B_u(r)). \]  \hspace{1cm} (2.5)

Equation [2.5] is important for the analysis of data taken by a scintillometer. The theory for scintillometers will be presented in more detail in Section 4.2. The power spectrum \( \Phi_u(\kappa) \) and the covariance \( B_u(r) \) are Fourier transform pairs by the Wiener-Khinchin theorem. In three-dimensions, the covariance is given by

\[ B_u(r) = \int \Phi_u(\kappa) e^{i\kappa \cdot r} d\kappa. \]  \hspace{1cm} (2.6)

For a homogenous and isotropic field, this expression can be reduced to

\[ B_u(r) = 4\pi \int_0^\infty \kappa \Phi_u(\kappa) \frac{\sin \kappa r}{r} d\kappa. \]  \hspace{1cm} (2.7)

The structure function \( D_u(r) \) for a homogeneous and isotropic field is related to the power spectrum by

\[ D_u(r) = 8\pi \int_0^\infty \kappa^2 \Phi_u(\kappa) \left( 1 - \frac{\sin \kappa r}{\kappa r} \right) d\kappa. \]  \hspace{1cm} (2.8)

where \( \kappa \) is a spatial frequency. The term in the parenthesis has properties of a high-pass filter. Spatial frequencies corresponding to separations larger than \( r \) are cut-off.

Kolmogorov uses the assumption of a locally homogenous and isotropic turbulence field, where turbulent flow consists of eddies of different sizes. For the largest eddies, the largest eddies being of the size of the atmospheric outer scale \( L_0 \), the directional information of the flow is still retained. These large eddies break up into smaller eddies in multiple processes, until the eddy motion is completely random\(^2\). All geometrical or directional information is lost and the energy is dissipated. The size of the smallest eddies is the inner scale \( l_0 \). \( L_0 \) is called the outer scale. The outer scale normally is of the size of tens of metres and the inner scale is of the size

\(^2\)The idea of cascading turbulence from large to small eddies was originally introduced by Richardson (1920).
2.2. Kolmogorov turbulence and the structure constant

of mm or cm. Both inner and outer scales increase monotonically with altitude. The outer scale also increases for stronger turbulence. For the phase shift of the light arriving at a telescope the outer scale is of greater importance, while for scintillation the inner scale has more impact (Andrews & Phillips 2005).

Since refractive image fluctuations cause a degradation of the image, for astronomy the refractive index structure function \( D_n(r) \) is the structure function of main interest. It describes and defines the strength of optical turbulence. Under the assumption of an isotropic atmosphere, a simple relation for the structure function and the separation \( r \) was found by Kolmogorov. The structure function scales with \( r^{2/3} \)

\[
D_n(r) = C_n^2 r^{2/3},
\]

where the constant \( C_n \), called the structure constant, depends on altitude. It is a measure of the local refractive index fluctuation. Kolmogorov (1941), working on the structure function of atmospheric wind velocity, realized that the structure function only depends on the modulus \( r \) (given in units of length, e. g. m) of the separation and on the energy dissipation rate per unit mass \( \epsilon \) (given in units of energy per time per mass, e. g. J/(s kg), which can be reduced to m\(^2\)/s\(^3\)). \( r \) and \( \epsilon \) only have units of velocity when combined as \( (r\epsilon)^{1/3} \). It follows that the structure function for velocity needs to be proportional to \( r^{2/3} \). Obukhov (1941) recognized the scaling law as being the same for all quantities, associated with the flow, such as temperature. Refractive index fluctuations mainly depend on temperature fluctuations, therefore the above scaling law is valid for the refractive index structure function, too. Since the fluctuations of the refractive index occur throughout the atmosphere, the integral of the structure constant over the entire atmosphere yields a measure of the quality of observing conditions. From knowledge of vertical \( C_n^2 \)-profiles, astronomical observing conditions can be deduced, as will be explained in section 2.3.1. For astronomical site testing, measurements of \( C_n^2 \)-profiles are important for assessing the quality of a site.

It should be noted that Equation 2.9 is only valid for the separation if \( r \) is smaller than the outer scale \( L_0 \) and greater than \( l_0 \). The power law changes for \( r \) being smaller than the inner scale (Tatarskii 1971). In addition, small deviations from the \( r^{2/3} \)-power law for the structure constant have been suggested, however these will not significantly change another key quantity.
derived for the treatment of optical turbulence - the power spectrum.

For Kolmogorov turbulence the power spectral density of refractive index fluctuations is given by the Kolmogorov power spectrum

\[ \Phi(k) = 0.033C_n^2\kappa^{-11/3}, \text{ for } 1/L_0 < \kappa < 1/l_0. \]  

(2.10)

The spectrum has a relatively-simple form and is only dependant on the structure constant. For integration over the entire spatial frequency spectrum, the outer scale sometimes is set to \( L_0 = \infty \) and the inner scale is set to \( l_0 = 0 \). This can lead to divergent integrals being non-physical. Von Karman realized the problem and modified Kolmogorov’s power spectrum for refractive index fluctuations. The spectrum is truncated by an exponential for large spatial frequencies \( \kappa \). In addition, a term with a minimal spatial frequency \( \kappa_0 \) was added, to account for the unknown behaviour of the spectrum at small frequencies. The von Karman power spectrum is given by (Andrews & Phillips 2005)

\[ \Phi_n(\kappa) = \frac{0.033C_n^2}{(\kappa^2 + \kappa_0^2)^{11/6}} \exp \left( -\frac{\kappa^2}{\kappa_m^2} \right), \]  

(2.11)

where \( \kappa_0 = 2\pi/L_0 \) and \( \kappa_m = 5.66/l_0 \).

In the next section atmospheric parameters for Astronomy will be introduced which depend on the structure constant, as the power spectrum does. The structure constant relates the power spectrum to atmospheric parameters. It carries the properties of the refractive index fluctuations. Knowledge of \( C_n^2 \)-profiles allows us to assess astronomical sites in terms of optical turbulence.

### 2.3 Atmospheric parameters for Astronomy

In order to determine the quality of observing conditions, there are parameters of special interest. These parameters depend on the atmospheric conditions and are often used for evaluating the quality of a site for a telescope or for evaluating system performance of an instrument. In this section the Fried parameter, the astronomical seeing, the isoplanatic angle and the atmospheric time constant are introduced. These parameters depend on the integral of the structure

\(^3\)The constant 0.033 in the formula is more accurately \( \Gamma(8/3) \sin(\pi/3)/(4\pi^2) \) (Roddier 1981).
constant or are integrals weighted by the structure constant. The parameters change with diurnal and annual cycles. For site testing campaigns the parameters need to be monitored over long periods to assess the potential of an astronomical site.

2.3.1 Fried parameter

The Fried parameter \( r_0 \) yields an aperture size over which the root-mean-square (rms) phase distortion equals one radian (Fried 1965). The Fried parameter is a measure for optical turbulence in the entire atmosphere and is calculated by an integration over the \( C_n^2 \)-profile,

\[
r_0 = \left[ \frac{0.42k^2}{\cos \gamma} \int_0^\infty C_n^2(z) \, dz \right]^{-3/5},
\]

(2.12)

where \( \gamma \) is the zenith angle. It is related to the phase structure function by

\[
D_\phi(r) = 6.88 \left( \frac{r}{r_0} \right)^{5/3}.
\]

(2.13)

The Fried parameter is dependent on the wavenumber and so it is related to the wavelength. From Equation 2.12 one can derive the following relationship between the Fried parameter and wavelength.

\[
r_0 \propto \lambda^{6/5}.
\]

(2.14)

The Fried parameter increases for increasing wavelength. Typical values are 10 - 20 cm in the visible. From Equation 2.1 it follows that the refractive index is independent of wavelength up to first order (Ageorges & Dainty 2000). Thus, the optical path difference is approximately the same for different wavelengths. The resulting phase shift is smaller for longer wavelengths, which facilitates wavefront correction for longer wavelengths.

2.3.2 Seeing

Seeing describes the inherent resolution of the turbulent atmosphere. Two nearby objects can be resolved if the angular separation between the objects exceeds the FWHM of the seeing-limited PSFs,

\[
\epsilon = 0.976 \frac{\lambda}{r_0}.
\]

(2.15)
2.3. Atmospheric parameters for Astronomy

The equation for seeing-limited resolution has a form that is similar to the equation for diffraction-limited resolution (Equation 1.2), the dependance on the aperture size for the diffraction-limited resolution being changed to the dependance on the Fried parameter for seeing-limited resolution. Telescopes without AO systems having aperture sizes of several meters can not reach their diffraction-limited resolution, since they are limited by the atmosphere. For a Fried parameter of 20 cm, a 10-m telescope can not reach a higher resolution than a 20-cm telescope. The 10-m telescope still has higher sensitivity, since it collects more photons, but it can not exceed the small telescope in angular resolution. From the comparison above, a second definition for the Fried parameter can be found. The Fried parameter defines the boundary aperture size between a telescope being diffraction-limited or seeing-limited in resolution. Telescopes having aperture sizes smaller than the Fried parameter are diffraction-limited, while telescopes having apertures larger than the Fried parameter are seeing-limited.

The example above demonstrates the importance of AO systems for large telescopes. AO systems mitigate the effects of the atmosphere and enable observations at the diffraction-limit for large telescopes. Seeing-limited PSFs are well-described by Moffat functions (Trujillo et al. 2001)

\[
PSF(r) = \frac{\beta - 1}{\pi \alpha^2} \left[1 + \left(\frac{r}{\alpha}\right)^2\right]^{-\beta},
\]

where \(r\) is the radius and \(\alpha\) is a parameter dependant on seeing. The Moffat function converges to a Gaussian distribution for \(\beta \rightarrow \infty\). When only atmospheric turbulence contributions are considered, the Moffat function yields the best fit to observed seeing-limited PSFs for \(\beta = 4.765\). Since imperfections in the optics of a telescope contribute to the PSF as well, the astronomical data reduction software IRAF uses \(\beta = 2.5\) as a default value. One advantage of a Moffat function over a Gaussian function is the ability to fit ‘wings’ appearing in the PSF. A comparison of the Moffat function for atmospheric turbulence contributions and a Gaussian can be seen in Figure 2.1.

2.3.3 Isoplanatic angle

Light propagating through the atmosphere has different optical paths for different angles of incidence. Each different optical path experiences different turbulent layers, resulting in different refractive index variations. The isoplanatic angle is the angle over which the index of refraction
The isoplanatic angle, like the Fried parameter is proportional to $\lambda^{6/5}$. When a binary system with angular separation less than the isoplanatic angle is observed, the image shows similar speckle patterns for both objects (Roberts Jr et al. 2005). The light propagates through similar turbulent layers, producing similar interference patterns. For AO systems anisoplanatism is one of the major problems reducing performance, since typical values for the isoplanatic angle are less than 5 arcsec. The guide star needs to be within this range from the science target for optical wavefront correction.
2.3.4 Atmospheric time constant

The atmosphere above the telescope is always in motion and the turbulent layers are constantly evolving. The Taylor frozen flow hypothesis assumes the horizontal movement of the atmosphere to be the dominating process (Taylor 1938). In comparison, the evolution of the distribution of the refractive indexes is slow compared to the time, it takes the flowing air to pass the field of view. The atmosphere can be modelled as thin rigid layers being blown horizontally at a certain wind speed $v$. By using $r = vt$ the structure function becomes time dependent. For a thin turbulent layer of thickness $\delta z$, the differential temporal structure function is

$$\delta D_n(t) = \frac{2.91k^2}{\cos \gamma} t^{5/3} C_N^2(z) v^{5/3}(z) \delta z .$$

(2.18)

Integration over the entire atmosphere yields the temporal structure function

$$D_n(t) = \frac{2.91k^2}{\cos \gamma} t^{5/3} \int_0^\infty C_N^2(z) v^{5/3}(z) dz ,$$

(2.19)

which can be simplified to

$$D_n(t) = \left( \frac{t}{\tau_0} \right)^{5/3} ,$$

(2.20)

where the atmospheric time constant is given by (Roddier 1981)

$$D_n(t) = \left[ \frac{2.91k^2}{\cos \gamma} \int_0^\infty C_N^2(z) v^{5/3}(z) dz \right]^{-3/5} .$$

(2.21)

From the atmospheric timescale, the Greenwood frequency can be derived. It is the minimum frequency at which the AO system needs to be updated (Greenwood 1977). Fried (1990) measured the Greenwood frequency to be on the order of 20-40 Hz. For closed-loop AO operation the update frequency of the system should be at least one order of magnitude higher than the Greenwood frequency.

2.4 Adaptive optics

Incoming wavefronts are continuously deformed by refractive index fluctuations in the atmosphere. The fluctuations are of random nature and blur the image of medium or large ground-based telescopes. Astronomers in modern times have always looked for sites where the effect
2.4. Adaptive optics

of wavefront distortion is minimal, resulting in observatories being built on high mountains. Chapter 3 and 4 review additional benefits of high mountain sites. While there are techniques of speckle imaging, providing angular resolution beyond the seeing limit, especially for telescopes with smaller diameter, the most useful technique for overcoming the seeing limit is AO. In the following, an introduction to adaptive optics will be given, highlighting technical aspects, capabilities, and unresolved difficulties. For detailed reviews of state of the art AO, the reader is referred to Hickson (2014), for a detailed description of atmospheric parameters and technical aspects of AO and to the review by Davies & Kasper (2012) which focuses on the impact of AO on observations in Astronomy.

Figure 2.2: Schematics of a closed-loop adaptive optics setup from Iqbal et al. (2009).

AO dates back to an idea by Babcock (1953) “If we had the means of continually measuring the deviation of rays from all parts of the mirror, and of amplifying and feeding back this information so as to correct locally the figure of the mirror in response to the schlieren pattern, we could expect to compensate both for the seeing and for any inherent imperfection of the optical figure”. AO systems compensate for the wavefront distortion introduced by Earth’s atmosphere by means of an optical system. It took more than 30 years before astronomers were able to demonstrate the feasibility of an AO system on a 1.5-m telescope, with infrared observations near the diffraction limit (Merkle et al. 1989; Rouset et al. 1990). The optical device used for
2.4. Adaptive optics

wavefront correction normally is a deformable mirror (DM) inserted in the beam after the primary mirror. The atmospheric distortion needs to be sensed in real time from a reference star, and the residual phase shift is passed to the DM. The surface of the DM is adjusted conjugate to the wavefront distortion, correcting the wave front. Figure 2.2 shows the principle setup of a basic AO system.

The performance of AO systems is measured in terms of the Strehl ratio. The Strehl ratio is the ratio of the peak intensity of the observed PSF, to the peak intensity of the PSF in a diffraction-limited case

\[
S = \frac{I_{\text{obs}}}{I_{\text{diff}}}. \tag{2.22}
\]

When observing at diffraction limit, the Strehl ratio equals 1. The flux intensity distributions for a seeing disc and the diffraction-limited Airy disc are shown in Figure 2.3. When the rms wavefront error is \( \sigma_M \approx \lambda/14 \), the Maréchal criterion is reached (Maréchal 1948). Then, the average wavefront error is 0.2 rad, which is significantly smaller than 1 rad for the Fried parameter. An image is “well-corrected” if \( S \geq 0.8 \), which is true for the Maréchal criterion. Without AO, telescopes operating at Strehl ratios of 0.8 or above are limited to diameter sizes of 0.4 \( r_0 \). For telescopes with aperture sizes much greater than the Fried parameter, phase aberrations can be considered random, since the wave is spread over a large area. Phase aberrations are gaussian-distributed and the Strehl ratio for small wavefront phase errors can be approximated by the Maréchal approximation

\[
S \approx \exp(-\sigma^2_\phi). \tag{2.23}
\]

Observations with AO do not necessarily achieve Strehl ratios greater than 0.8. Later we will see that only a small percentage of the observations are carried out having these high Strehl ratios. The benefit from observations with adaptive optics can be inferred by comparing resolution and sensitivity for observations with and without it. In the best case, observations with AO are near the diffraction limit.

For a 30 m-class telescope operating at the diffraction limit, the resolution is 100 times higher than in excellent seeing conditions, assuming a Fried parameter of 30 cm. An example image comparing the resolution of observations with and without AO is shown in Figure 2.4. But
not only does the resolution increase, when AO is used, sensitivity increases, as well. In general for telescopes, the sensitivity scales with $D^2$ due to the increase in area of the aperture. For observations with adaptive optics, photons which would fall into the boundary areas of the seeing disc are concentrated in the inner part of the Airy disc. The PSF is contained to a smaller area on the detector, which yields a decrease in background noise by another factor of $D^2$, resulting in higher signal to noise ratios. Overall, the sensitivity increases by a factor of $D^4$ for observations with AO of faint unresolved sources.

AO systems use natural guide stars (NGS) or artificial guide stars in the field of view to sense atmospheric distortion. NGS are natural stars of sufficient-brightness close to the science object. The second and third types of guide star are both laser guide stars (LGS), in which a laser is pointed towards the atmosphere and the back-scattered light is used to sense the wavefront correction. In the lower atmosphere between 10 and 20 km, the light is Rayleigh-scattered from atoms or molecules. In the case where Rayleigh-scattered light is used for wavefront correction, the LGS is called Rayleigh LGS. Rayleigh LGS are well-suited for sensing and correcting the

![Figure 2.3: Cross section through an image showing the PSF of the seeing disk and the PSF in the diffraction-limited case.](image)
2.4. Adaptive optics

Figure 2.4: Neptune observed with and without AO on the Very Large Telescope. The images were taken at visible wavelengths during the commissioning of the integral-field spectrograph MUSE/GALACSI. Credit: ESO/P. Weilbacher (AIP)

lower atmosphere on smaller telescopes. The setup and equipment for a Rayleigh LGS is the least expensive and the least complex, of the two. For a sodium LGS, the laser is tuned to the sodium $D_2$-line and excites neutral sodium in the mesosphere. There is a layer of neutral sodium between 80 and 120 km, and once excited by a laser it becomes fluorescent. This fluorescent column of neutral sodium viewed from the earth directly below, appears star-like. The sodium is deposited by meteor ablation, and slowly sinks towards the lower boundary of the layer. At the lower boundary, the higher air density allows the sodium to react with oxygen or nitrogen. Besides sodium, in the mesosphere there are four other plentiful elements that could be used for the creation of LGS. These elements are iron, potassium, calcium and magnesium. Sodium is used, as the sodium $D_2$ line yields the highest product of cross-section and element abundance which determines the strength of the return flux. Values for the sodium column-density typically are on the order of $10^{13}$ m$^{-2}$. The sodium column-density shows seasonal and diurnal trends. Seasonal trends are more noticeable with increasing latitude. During winter months the column density is the highest and can be four times the minimum column density in summer months. The seasonal trends are mitigated towards the equator, but show similar behaviour in the southern hemisphere. During the night the sodium abundance is minimal.
2.4. Adaptive optics

Around midnight, while it is the greatest during the hours of dusk and dawn.

For the scope of the thesis, I will mainly focus on sodium LGS. Next generation extremely-large telescopes will be using AO systems with sodium LGS in combination with NGS. Sodium LGS, being positioned in the mesosphere, are used for large telescopes, since their wave front aberration depicts the entire atmosphere and the effect of focal anisoplanatism, also called cone effect, is mitigated, in comparison to Rayleigh LGS. Light falling on the telescope spans a cone between the LGS and the primary mirror, while the light from the science object spans a column. For a LGS at higher altitude, the cone of the LGS will have greater coverage in the lower atmosphere, where most of the turbulence is located. The cone effect scales with telescope aperture size, which is another reason for sodium LGS being better suited for large telescopes. The guide star being not-aligned with the science object, results in another type of anisoplanatism, angular anisoplanatism. The light of the guide star is not propagated along the exact same path through the atmosphere as the light from the science object, so it ‘sees’ a slightly different part of the atmosphere. Angular anisoplanatism limits the useful field of view of AO systems in cases where only NGS are being used. Figure 2.5 shows focal and angular anisoplanatism. If only NGS are used for wavefront sensing, the NGS should not be fainter than 12th magnitude (Gardner et al. 1990), to allow for sufficient-fast update rates of the AO system. However, it is

![Figure 2.5: Focal and angular anisoplanatism.](image)
2.4. Adaptive optics

It is not always possible to find bright stars in the field of view. Since sodium LGS can be created anywhere on sky, AO systems operating with LGS yield increased sky coverage (Ellerbroek & Tyler 1998). Figure 2.6 shows the increased sky coverage for observations with LGS. Sodium LGS typically have magnitudes of about 7.

Figure 2.6: Simulated sky coverage in different observing bands at the Gemini-North Telescope for AO systems using NGS and LGS. AO systems with LGS increase the fraction of the sky which can be observed with higher Strehl ratios. Adapted from Ellerbroek & Tyler (1998) ©The Astronomical Society of the Pacific. Reproduced with permission. All rights reserved. https://iopscience.iop.org/article/10.1086/316120/meta

Sodium LGS are also affected by angular anisoplanatism. In order to mitigate the effect, some AO systems employ multiple LGS. The lowest order aberrations, tip and tilt, cannot be sensed with LGS. The roundtrip from the laser to the sodium layer and back to the laser for the light takes on the order of approximately 0.6 ms for observations near zenith. In contrast, if the LGS
is created and observed in a monostatic configuration (the same telescope launches the laser and observes the LGS) the time for the tip-tilt aberration to change is on the order of a few ms. If the LGS is created in a bistatic configuration (separate telescopes launch the laser and observe the LGS) then the measured LGS tilt combines different uplink and downlink tilts, where the uplink tilt is unknown as well. By including a NGS for tip-tilt correction, the problem can be overcome. The NGS only experiences downlink tilt. So NGS are used for tip-tilt correction. In addition to tip-tilt correction NGS are used for atmospheric focus sensing. These low order aberrations change slowly, allowing for lower update frequencies in the AO system. Fainter NGS can be used for sensing of tip-tilt and atmospheric focus correction.

From Equation 2.1, it follows the index of refraction is dependant on wavelength. Light of greatly-different wavelengths is bent differently during propagation through the atmosphere. Using a polychromatic LGS, tip and tilt could be sensed, negating the need for NGS. Different concepts for polychromatic LGS have been considered and investigated, but to the knowledge of the author, tip-tilt correction from a polychromatic LGS has not been successfully demonstrated.

Having discussed guide stars to some extent, we will now turn our attention towards wavefront sensing and correction in AO systems. AO systems normally are run in “closed-loop” mode, where the wavefront distortion is sensed after the light passes the DM. Systems where the wavefront is sensed before the DM are called “open loop”, where the path of the light is split without any feedback loop. “Closed-loop” operation of AO systems is superior in terms of system performance [Ragazzoni & Farinato 1999]. In the optics of the telescope the light of the science object and the LGS are overlaid. The light of the science object is separated by a beam splitter. The light of the LGS is directed towards a wavefront sensor, where the aberration is expanded in Zernike or planar modes and a control system controls the actuators of the DM. For controlling the surface of the DM different technologies can be used, e.g. piezoelectric crystals or micro-electrical-mechanical actuators. There are two different conceptual designs for wavefront sensors shown in Figure 2.7. The Shack-Hartmann wavefront sensor is a lenslet array that allows us to measures the wavefront aberration from the position of the light in the focal plane of the lenses. A planar wavefront falling on the lenslet array would form focal spots in the centre under each lens. For a distorted wave, the spots would move around and be positioned off-center. The pyramid wavefront sensor [Ragazzoni 1996] is a pyramid-shaped prism moving in a plane perpendicular to the beam. The light is focused on a detector.
2.4. Adaptive optics

by a collimating lens. From sensor and detector position the wavefront deformation can be computed. The pyramid sensor achieves higher performance for non-elongated LGS and can correct over the entire aperture. And it can respond non-linearly, since the speed for the sensor to move can be adjusted. The Shack-Hartmann wavefront sensor is better suited for elongated LGS, and is more robust, since it does not have any moving elements, but the sensitivity of the Shack-Hartmann wavefront sensor is limited by the diffraction limit of the sub-aperture size, while the sensitivity of the pyramid wavefront sensor is limited by the size of the entire aperture (Esposito & Riccardi 2001).

The waveform is represented in zonal or Zernike modes. Zernike functions form a complete set of an orthogonal basis over the area of a unit circle (Noll 1976). If polar coordinates $r$ and $\theta$ are used, the Zernike functions are a product of radial polynomials and angular functions. They are symmetric under rotation and can be expressed by
2.4. Adaptive optics

Figure 2.8: Lowest-order Zernike polynomials. Reprinted with permission from Schwiegerling, J., *Review of Zernike polynomials and their use in describing the impact of misalignment in optical systems*, 2017, in Optical System Alignment, Tolerancing, and Verification XI, Vol. 10377, International Society for Optics and Photonics, 103770D.

\[
Z_{\text{even}} = \sqrt{n+1} R_{\text{even}}^m (r) \sqrt{2} \cos m\theta, \quad \text{for } m \text{ even}
\]

\[
Z_{\text{odd}} = \sqrt{n+1} R_{\text{odd}}^m (r) \sqrt{2} \sin m\theta, \quad \text{for } m \text{ odd}
\]

\[
Z_0 = \sqrt{n+1} R_0^n (r), \quad \text{for } m = 0
\]

where

\[
R_{n}^m (r) = \sum_{s=0}^{(n-m)/2} \frac{(-1)^s(n-s)!}{s![(n+m)/2-s]!(n-m)/2-s)!} r^{n-2s}.
\]

\(n\) is the degree of the radial polynomial and \(m\) is the azimuthal frequency. \(n\) and \(m\) need to always satisfy the following relations \(|m| \leq n\) and \(n - |m| = \text{even}\). There is a direct, but neither obvious nor trivial, connection between Zernike modes and turbulence. The phase spectrum of turbulence can be expressed in a Zernike representation. The lowest orders of Zernike modes,
2.4. Adaptive optics

represent piston\footnote{Piston can not be sensed with AO systems.} and the classical Seidel aberrations tip, tilt, (de)focus, astigmatism, coma and spherical aberration. Figure 2.8 gives an overview of the lowest-order Zernike polynomials.
Chapter 3

Weather at selected astronomical sites - an overview of five atmospheric parameters

Since atmospheric conditions have a strong impact on observing conditions, prior to the construction and commissioning of a telescope, the site for the telescope has to be wisely chosen. The sites under consideration are evaluated by general climatological data and in-situ site testing campaigns. In this chapter an analysis of meteorological data is presented. In the following chapter site testing measurements of $C_N^2$-profiles will be shown and an introduction to in-situ site testing of optical turbulence is given.

Global weather data can yield a first estimate of average observing conditions. They can serve as baseline data to compare expected observing conditions either between already-existing observatories or new telescope projects to already-existing observatories. A version of this chapter has been previously published as J. Hellemeier, R. Yang, M. Sarazin and P. Hickson Weather at selected astronomical sites - an overview of five atmospheric parameters in Monthly Notices of the Royal Astronomical Society, Vol. 482, 2018.

3.1 Introduction

Atmospheric conditions have a major impact on the quality of observations in ground-based astronomy. Before selecting a site for a new facility, extensive site-testing campaigns are often conducted \cite{Schoeck2009,Vernin2011}. In evaluating the quality of a site, weather, astronomical seeing, turbulence distribution and extinction are important considerations. Key parameters relating to weather include the fraction of photometric and spectroscopic nights,
3.2 Sites and atmospheric parameters

Site testing employs a variety of different instruments to probe the atmosphere. The differential image motion monitor (DIMM) measures the integrated seeing (Sarazin & Roddier 1990). The multi-aperture scintillation sensor (MASS) provides an estimate of the contribution to seeing from turbulence in six levels of the atmosphere (Tokovinin 1998; Kornilov et al. 2003). Measurements of the index-of-refraction structure constant $C_n^2$ yield estimates of the overall seeing due to turbulence. Acoustic (SODAR) and optical (SHABAR) instruments measure $C_n^2$ profiles in the atmospheric ground-layer (Beckers 1993; Hickson & Lanzetta 2004; Hill et al. 2006; Hickson et al. 2010a; Lombardi et al. 2010), while SCIDAR and SLODAR can probe the entire atmosphere (Vernin & Roddier 1973; Wilson 2002; Masciadri et al. 2010). Other site characteristics such as dust and light pollution are also important. These campaigns provide a wealth of data, but it is often difficult to compare different sites due to the heterogeneity of the instruments and techniques employed. This paper presents an analysis of weather data from the ESO FriOWL database (Graham et al. 2004; Sarazin et al. 2006) for fifteen observatory sites. The results complement in-situ measurements by site testing campaigns, and provide a comparison of weather at different sites that should be uniform and unbiased.

3.2 Sites and atmospheric parameters

For this study, fifteen sites were selected, spread over five continents. Many of these sites host world-class optical observatories; others are considered as potential sites for future telescope projects. Ascension Island is also included as an example of a low-altitude low-latitude site hosting optical telescopes (Lederer et al. 2016). Table 3.1 and the map in Figure 3.1 give an overview of the sites.

3.2.1 FriOWL database

The FriOWL project was founded to aid in the site selection process for ESO’s European Extremely Large Telescope. It aimed to consolidate available meteorological data in order to create a useful site selection tool (Graham et al. 2008). The project’s database comprises the meteorological data sets ERA-40, NCEP-NCAR, NOAA, CGCM1, TOMS, GSHAP and USGS.
3.2. Sites and atmospheric parameters

![Map of observatory sites](image)

Figure 3.1: Overview of the geographical locations of the observatory sites. Elevation, longitude and latitude of the sites are shown in Table 3.1.
3.2. Sites and atmospheric parameters

Table 3.1: Information on observatory sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Country</th>
<th>Elevation (m)</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ali</td>
<td>China</td>
<td>5200</td>
<td>32.30 N</td>
<td>80.05 E</td>
</tr>
<tr>
<td>Ascension</td>
<td>Ascension Isl.</td>
<td>150</td>
<td>7.93 S</td>
<td>14.42 W</td>
</tr>
<tr>
<td>C. Pachon</td>
<td>Chile</td>
<td>2715</td>
<td>30.24 S</td>
<td>70.73 W</td>
</tr>
<tr>
<td>C. Paranal</td>
<td>Chile</td>
<td>2635</td>
<td>24.63 S</td>
<td>70.40 W</td>
</tr>
<tr>
<td>Chajnantor</td>
<td>Chile</td>
<td>5050</td>
<td>23.02 S</td>
<td>67.75 W</td>
</tr>
<tr>
<td>DAG*</td>
<td>Turkey</td>
<td>3100</td>
<td>39.78 N</td>
<td>41.23 E</td>
</tr>
<tr>
<td>Devasthal</td>
<td>India</td>
<td>2450</td>
<td>29.37 N</td>
<td>79.68 E</td>
</tr>
<tr>
<td>Dome A</td>
<td>Antarctica</td>
<td>4093</td>
<td>80.37 S</td>
<td>77.35 E</td>
</tr>
<tr>
<td>Dome C</td>
<td>Antarctica</td>
<td>3232</td>
<td>75.10 S</td>
<td>120.33 E</td>
</tr>
<tr>
<td>Hanle</td>
<td>India</td>
<td>4500</td>
<td>32.79 N</td>
<td>78.96 E</td>
</tr>
<tr>
<td>La Palma</td>
<td>Spain</td>
<td>2350</td>
<td>28.76 N</td>
<td>17.89 W</td>
</tr>
<tr>
<td>Maidanak</td>
<td>Uzbekistan</td>
<td>2600</td>
<td>38.68 N</td>
<td>66.93 E</td>
</tr>
<tr>
<td>Mauna Kea</td>
<td>USA</td>
<td>4207</td>
<td>19.82 N</td>
<td>155.47 W</td>
</tr>
<tr>
<td>Mt. Graham</td>
<td>USA</td>
<td>3191</td>
<td>32.70 N</td>
<td>109.88 W</td>
</tr>
<tr>
<td>Siding Spring</td>
<td>Australia</td>
<td>1165</td>
<td>31.27 S</td>
<td>149.06 E</td>
</tr>
</tbody>
</table>

* Dogu Anadolu Gözlemevi

For our analysis only ERA-40 and TOMS data are used.

ERA-40 data are the result of a re-analysis of various climatological data obtained over the period 1957 to 2002 (Uppala et al. 2005). The re-analysis takes advantage of more advanced surveying methods that became available, providing improved meteorological characteristics. In FriOWL, ERA-40 data are available on a grid with 2.5°×2.5° resolution, which corresponds to a 278×278 km resolution at the equator and to a 278×48 km resolution at 80° latitude. The TOMS data set was obtained by the NASA Total Ozone Mapping Spectrometer. The spectrometer was operated on three different satellites between 1979 and 2005. Its main purpose was the mapping of the ozone layer, but as a byproduct the aerosol contamination in the atmosphere can be inferred from the data (Torres et al. 1998). TOMS data are available with a resolution of 1°×1.25° for latitudes between 60° N and 60° S.

3.2.2 Atmospheric parameters

FriOWL provides data for different pressure levels of the atmosphere, and surface data. We do not use the surface data, as the 2.5° tiles of the grid comprise multiple geological features, and
3.2. Sites and atmospheric parameters

the elevation of the site is unlikely to coincide with the averaged altitude within the tile. For quantities dependent on the pressure $P$, data sets for multiplies of 100 hPa are available. We convert these pressure levels to altitude $a$, in metres, via the relation

$$a = 128 - 19147x - 4292x^2 - 1275x^3,$$  \hspace{1cm} (3.1)

where $x = \log(P/100 \text{ hPa})$. This equation was obtained by fitting a third-order polynomial to tabulated values of the international standard atmosphere (Kasten & Young 1989). It has an RMS error of 45 m from −2 km to 30 km altitude and is rarely in error by more than 100 m. The pressure level that was used for each site is the one for which the corresponding altitude is closest to that of the site.

Cloud cover: The ERA-40 data cover the period September 1957 to August 2002 and provide high-level (above 6000 m), mid-level (2000 − 6000 m) and low-level (below 2000 m) cloud-cover fractions. The cloud cover was computed for the times 6:00, 12:00, 18:00 and 24:00 UTC. In estimating the cloud cover for each site, we used the average of the values listed for the two times that occurred during local night time. For sites between 2000 and 6000 m, only the high-level and mid-level cloud fractions were used. The total cloud-cover fraction $f_c$ then was estimated by multiplying the mid-level cloud cover (mcc) fractions by the fraction of the mcc altitude interval that lies above the altitude $a$ of the observatory, and adding to this the fraction of high-level cloud (hcc),

$$f_c = \frac{6000 \text{ m} - a}{4000 \text{ m}} f_{\text{mcc}} + f_{\text{hcc}}. \hspace{1cm} (3.2)$$

For sites below 2000 m a similar approach was taken, including the low-level cloud cover (lcc)

$$f_c = \frac{2000 \text{ m} - a}{2000 \text{ m}} f_{\text{lcc}} + f_{\text{mcc}} + f_{\text{hcc}}. \hspace{1cm} (3.3)$$

The coarse resolution of ERA-40 data limits the depiction of cloud conditions in an area with a complex topography, such as the caldera on La Palma. As a check, the cloud cover obtained by the method described above was compared with in-situ records of photometric nights at Cerro Paranal and La Silla (ESO 2018). Figures 3.2 and 3.3 present a comparison of clear-sky fraction $1 - f_c$ with the fraction of photometric nights. Requiring a night to be photometric is a more restrictive condition, as no clouds can be present. Hence the photometric fraction is lower than the clear-sky fraction. Nevertheless, the same trends can be seen in both parameters, with
photometric fraction being typically 60-80% of the clear-sky fraction.

**Wind speed at 200 hPa:** It is known that optical seeing correlates with the wind speed at the 200 hPa pressure level, approximately 12 km above sea level (Vernin 1986, Sarazin & Tokovinin 2002). This arises because wind shear associated with strong upper-level winds produces high-level turbulence. This increases the contribution of the free atmosphere (i.e. excluding turbulence in the planetary boundary-layer and ground layer) to the seeing. The 200 hPa wind speed is therefore an important parameter for the assessment of the potential for astronomical sites. For a Kolmogorov turbulence spectrum, seeing FWHM $\epsilon$ is related to the Fried parameter $r_0$ and the turbulence integral $J$ by the relations (Fried 1966, Roddier 1981)

$$\epsilon = 0.976 \frac{\lambda}{r_0},$$

$$r_0^{-5/3} = 0.423 k^2 J,$$

$$J = \int C_n^2(z) dz,$$

where $z$ is the distance along the line of sight, $k = 2\pi/\lambda$ is the optical wavenumber and $\lambda$ is the wavelength, conventionally taken to be 500 nm. Atmospheric observations indicate that above a transition wind speed of about 1 m s$^{-1}$, turbulent velocities produced by wind shear are roughly proportional to wind speed (Mahrt et al. 2013). Thus one would expect that the high-level contribution to the turbulence integral will be proportional to the square of the 200-hPa wind speed $u_{200}$. The turbulence integral can be written as the sum of upper and lower contributions,

$$J = J_{\text{lower}} + J_{\text{upper}}.$$  

The upper contribution should be roughly proportional to the square of the 200-hPa wind speed,

$$J_{\text{upper}} \sim A u_{200}^2,$$

where $A$ is a constant. By correlating measurements of atmospheric seeing with 200-hPa wind speed, it is possible to estimate the value of the proportionality constant $A$, and thereby determine the contribution of the upper-level turbulence to the seeing. This is of particular interest for telescopes employing ground-layer adaptive optics (GLAO), which can greatly reduce the lower-level contribution. In that case, the image quality will be dominated by the upper-level
3.2. Sites and atmospheric parameters

Figure 3.2: Comparison of ERA-40 clear-sky fraction \((1 - f_c)\) with the fraction of photometric nights at Cerro Paranal (above) and La Silla (below). The data shown are monthly averages covering the years 1983 - 2002. La Silla is an additional site in Chile in the proximity to Cerro Pachon.
3.2. Sites and atmospheric parameters

Figure 3.3: Correlation of monthly-averaged cloud-cover data and photometric nights. The data for the correlation are shown in Figure 3.2.

turbulence. In FriOWL, the 200-hPa wind speed is retrieved directly from ERA-40 data.

Precipitable water vapour: Water vapour in the atmosphere absorbs incoming infra-red radiation. The precipitable water vapour (PWV) describes the mass of the water for a column of unit size integrated from a certain pressure level to the upper boundary of the atmosphere. PWV is of major interest for telescopes operating at mid-infrared and sub-millimetre wavelengths as it is the dominant source of atmospheric opacity beyond a wavelength of 5 μm (Chamberlin 2001; Otárola et al. 2010). PWV for different altitudes is not directly provided by the ERA-40 dataset, but can be estimated according to the prescription in Graham et al. (2008). Essentially, the local water vapour density is calculated, for different pressure levels, from humidity data provided by ERA-40. An estimate of the PWV can then be obtained by integration.

Vertical wind velocity: The vertical wind velocity in the lower troposphere is related to buoyancy and static stability. In the absence of forced mountain upslope, downslope or katabatic winds, vertical velocities reveal the stability or instability of the airmass, which has important implications in the generation of turbulence (Monin & Obukhov 1954). Vertical motion changes the temperature by adiabatic warming and cooling of the air through descent and ascent, re-
3.3 Results & Discussion

respectively. Thériault & Stewart (2007) demonstrated that even very weak upward vertical air velocity ($\leq 10$ cm/s) significantly influences the types and amount of precipitation formed in the atmosphere. A larger ascending air velocity is associated with more precipitation at the surface. The FriOWL database gives vertical wind speed for different pressure levels for the years 1989 – 2009. Thus the vertical velocity can be estimated for each of the sites. By convention, vertical velocity is positive for descending air and negative for rising air (Graham et al. 2008).

**Aerosol index:** Observatories are often placed in warm, high, dry locations. This brings a risk of aerosol contamination of the atmosphere, due largely to wind-blown dust. There is a clear correlation between atmospheric extinction and aerosol abundance (Siher et al. 2004). Aerosols not only influence the sky transparency but also degrade the equipment (especially optical mirror coatings) (Giordano & Sarazin 1994). The aerosol data set in FriOWL was derived from TOMS data for the years 1980 – 2002. Torres et al. (1998) have verified a method for determining the aerosol index from TOMS data. TOMS data provide the intensity due to Mie scattering from particles of smoke, desert dust and volcanic ash (Herman et al. 1997). The index $a_i$ is found by relating the measured intensity of the scattered radiation to that expected for Rayleigh scattering alone,

$$ a_i = 100 \log_{10} \left( \frac{I_{m,0.36}}{I_{c,0.36}} \right), $$

where $I_{m,0.36}$ is the radiance measured at a wavelength $\lambda = 0.36$ $\mu$m and $I_{c,0.36}$ is the expected intensity, at this wavelength, for Rayleigh scattering. The aerosol index is $a_i = 0$ for an atmosphere having no aerosol contamination and is positive for absorbing aerosol contamination (Torres et al. 2002).

3.3 Results & Discussion

This section provides a summary of results for each individual parameter. All data sets can be found in Appendix 9. Yearly averages of the quantities studied are shown in Table 3.2.

3.3.1 Cloud cover

The cloud-cover fractions for the sites are shown in Figure 3.4. Ascension Island, the lowest-altitude site, has the highest annual average cloud cover, with little seasonal variation. The two Antarctic sites have cloud-cover fractions of $f_c \sim 0.2$ throughout the year, with a high of $\sim 0.4$
3.3. Results & Discussion

Figure 3.4: Monthly averages of the calculated fractional cloud cover, for the period September 1957 – August 2002. Cloud-cover fractions greater than 1 can arise if multiple cloud layers are present.
3.3. Results & Discussion

Table 3.2: Yearly averages for cloud-cover fraction $f_c$, 200 hPa wind speed $u_{200}$, precipitable water vapour PWV, vertical wind velocity $v$ and aerosol index $a_i$.

<table>
<thead>
<tr>
<th>Site</th>
<th>$f_c$ [m/s]</th>
<th>$u_{200}$ [kg/m²]</th>
<th>PWV [cm/s]</th>
<th>$v$ [m/s]</th>
<th>$a_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ali</td>
<td>0.21±0.05</td>
<td>29.03±3.40</td>
<td>3.02±0.66</td>
<td>0.83±0.76</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>Ascension</td>
<td>0.53±0.01</td>
<td>8.77±0.70</td>
<td>7.91±0.66</td>
<td>3.71±0.16</td>
<td>2.37±0.62</td>
</tr>
<tr>
<td>C. Pachon</td>
<td>0.14±0.02</td>
<td>32.16±1.10</td>
<td>3.24±0.11</td>
<td>-10.44±0.44</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>C. Paranal</td>
<td>0.08±0.01</td>
<td>29.89±2.07</td>
<td>2.70±0.16</td>
<td>0.04±0.22</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>Chajnantor</td>
<td>0.16±0.03</td>
<td>25.46±2.55</td>
<td>1.06±0.13</td>
<td>8.91±1.37</td>
<td>0.28±0.15</td>
</tr>
<tr>
<td>DAG</td>
<td>0.47±0.05</td>
<td>23.30±1.42</td>
<td>5.18±0.53</td>
<td>-0.22±0.36</td>
<td>0.09±0.08</td>
</tr>
<tr>
<td>Devasthal</td>
<td>0.40±0.09</td>
<td>28.73±4.77</td>
<td>11.22±2.10</td>
<td>-5.44±2.42</td>
<td>0.04±0.04</td>
</tr>
<tr>
<td>Dome A</td>
<td>0.28±0.02</td>
<td>4.25±0.35</td>
<td>0.26±0.05</td>
<td>1.02±0.16</td>
<td>n.a.</td>
</tr>
<tr>
<td>Dome C</td>
<td>0.28±0.02</td>
<td>8.21±0.71</td>
<td>0.47±0.08</td>
<td>0.40±0.04</td>
<td>n.a.</td>
</tr>
<tr>
<td>Hanle</td>
<td>0.27±0.05</td>
<td>29.03±3.41</td>
<td>6.64±1.33</td>
<td>1.29±0.57</td>
<td>0.10±0.07</td>
</tr>
<tr>
<td>La Palma</td>
<td>0.17±0.03</td>
<td>19.44±1.37</td>
<td>3.25±0.19</td>
<td>5.29±0.47</td>
<td>1.51±0.75</td>
</tr>
<tr>
<td>Maitanak</td>
<td>0.37±0.07</td>
<td>27.56±0.89</td>
<td>4.61±0.42</td>
<td>-5.29±0.51</td>
<td>0.03±0.03</td>
</tr>
<tr>
<td>Mauna Kea</td>
<td>0.25±0.01</td>
<td>21.74±1.77</td>
<td>2.22±0.07</td>
<td>3.23±0.13</td>
<td>0.44±0.15</td>
</tr>
<tr>
<td>Mt. Graham</td>
<td>0.26±0.02</td>
<td>23.21±2.50</td>
<td>5.49±0.97</td>
<td>-1.74±0.66</td>
<td>0.11±0.07</td>
</tr>
<tr>
<td>Siding Spring</td>
<td>0.40±0.01</td>
<td>31.29±2.29</td>
<td>6.73±0.74</td>
<td>0.45±0.52</td>
<td>0.00±0.00</td>
</tr>
</tbody>
</table>

during the southern winter. Mauna Kea shows similar values, with little seasonal fluctuation. La Palma has very-low cloud cover during the summer, and is comparable to Mauna Kea the rest of the year. Siding Spring shows a cloud cover of $\sim 0.4$ with little seasonal variation. For DAG and Maidanak the cloud-cover fraction is $\sim 0.6$ in winter, and decreases to $\sim 0.1 - 0.2$ during the summer months. Cerro Paranal has the best conditions through the entire year with values near $f_c \sim 0.1$. Chajnantor has low cloud cover during the southern winter and high cloud cover in the southern summer while Cerro Pachon has the lowest cloud cover in the southern summer and a slight increase for the winter month. The increased cloud cover for Chajnantor results from the weather phenomena called “Bolivian winter”. During the summer months an area of extensive cloud forms over Bolivia and is pushed to the south by the prevailing winds. The Asian sites in our sample are all impacted by the monsoon, which results in high cloud-cover fractions during the summer months. Devasthal, in the southern foothills of the Himalayas, is most-strongly affected. Conditions are better in the winter, with Ali and Hanle showing very low cloud-cover fractions during that season.
Figure 3.5: Monthly averages of the wind speed at 200 hPa. Averages have been taken for ERA-40 data in the period from September 1957 to August 2002. Hanle and Ali have the same values. They are located on the same grid point and the elevation of the observatory does not have an impact on the wind speed at 200 hPa.

3.3.2 200-hPa wind speed

Plots of 200-hPa wind speed are shown in Figure 3.5. As expected, the upper-level wind velocities are highest for mid-latitude sites. The polar and equatorial sites show the lowest velocities over the entire year, typically less than 10 m s\(^{-1}\). In contrast, all sites located on major continents show a seasonal dependency, varying in extent with latitude. At low latitudes the jet stream is strong during winter and moves towards the poles in the summer months (Qing-cun et al., 1986). Only for DAG does the 200-hPa wind speed increase during the summer. The sites close to the Himalayan central chain, such as Ali, Devasthal and Hanle, show the strongest variation. The sites in the Andes show a steady behaviour with relatively low wind velocity during the summer and an increase in winter. Cerro Pachon does have relatively high values
for the summer, compared to Cerro Paranal and Chajnantor. The islands of Hawaii and La Palma have relatively steady upper-level winds throughout the year.

### 3.3.3 Precipitable water vapour

The results for PWV can be seen in Figure 3.6. As expected, PWV depends strongly on the geographical location and the altitude of the telescope site. The sites on the Asian continent show a strong increase during the summer months due to the influence of the monsoon. The impact is greatest for lower-altitude observatories such as Devasthal. For the high-altitude, more northerly sites, the influence of the monsoon is smaller. Mount Graham has a moderately humid summer also. Ascension Island and Siding Spring, both relatively-low altitude sites, show high PWV values over the entire year. Mauna Kea, La Palma, and Chilean sites, and especially the Antarctic sites have low values throughout the year.

![Figure 3.6: Monthly averages of the PWV. The data are from ERA-40 for the period September 1957 – August 2002.](image-url)
3.3. Results & Discussion

Figure 3.7: Monthly averages of the vertical wind velocity for ERA-40 data, for the period September 1957 to August 2002.

3.3.4 Vertical wind velocity

The results for the monthly-averaged vertical wind velocity can be seen in Figure 3.7. Dome A, Dome C and Siding Spring show the smallest average values for vertical wind over the entire year. In southern Asia, vertical wind velocity is strongly influenced by the monsoon (Uma et al., 2012). Devasthal has high negative vertical wind velocities (rising air) during the summer. The impact of the monsoon is lower for Ali, located north of the main Himalayan mountain range, and vanishes for Hanle, which is a high, dry, site. The Chilean sites show an interesting behaviour. At Chajnantor the vertical wind velocity is positive all year round, while at C. Pachon it is negative and at C. Paranal it is close to zero. Maidanak experiences rising air over the entire year, as well. Mt. Graham, Mauna Kea, Ascension Island, La Palma and DAG show relatively steady and unremarkable vertical wind velocities over the year.
3.3. Results & Discussion

3.3.5 Aerosol index

Figure 3.8: Monthly averages for the aerosol index over the year 1980 – 2002. Dome A and Dome C are not included because the TOMS data only covers latitudes between 60° S and 60° N.

The results for the monthly averages of the aerosol index can be seen in Figure 3.8. Averages were taken for TOMS data from January 1980 to December 2002. La Palma and Ascension Island being the closest to the Sahara desert, show the highest abundance of aerosols. La Palma has high aerosol contamination during the summer, when dust from the Sahara desert is transported by easterly winds to the Canary Islands. This phenomenon is called “La Calima”. Ascension Island experiences aerosol contamination from December to April and also from June to October. The contamination is greatest in January and February but is lower than the peak contamination on La Palma. The other sites have significantly lower aerosol indexes. Mauna Kea has some contamination from March until August. Chajnantor is the only Chilean site experiencing significant aerosols (from September until December). All other sites show very-low aerosol indexes.
3.3. Results & Discussion

3.3.6 Correlations

Weak correlations were found between cloud cover, wind speed at 200 hPa and precipitable water vapour with site latitude and altitude. The correlation coefficients for Pearson correlation $r_p$, Kendall correlation $\tau_k$ and Spearman correlation $\rho_s$ were determined and are shown in Table 3.3. Pearson correlation tests for a linear relation between the datasets (Lawrence & Lin 1989), while Kendall and Spearman correlation are non-parametric statistics testing for rank correlation (Croux & Dehon 2010). Cloud cover and PWV both tend to decrease with altitude (Figure 3.9 and Figure 3.10). High-level winds are greatest at mid-latitude sites, due to the impact of the subtropical jet stream (Figure 3.11). For the three correlations the absolute of the Pearson correlation coefficient $r_p$ is greater than 0.5 and the probabilities for uncorrelated datasets having these Pearson correlation coefficients is below 5%.
3.3. Results & Discussion

Figure 3.10: Correlation of yearly averages of precipitable water vapour and site altitude. Values of the Pearson correlation coefficient $r_p$, the Kendall correlation coefficient $\tau_k$ and the Spearman correlation coefficient $\rho_s$ are shown.

Table 3.3: Correlation coefficients for Pearson correlation $r_P$, Kendall correlation $\tau_K$ and Spearman correlation $\rho_S$. The associated p-values yield the probability for an uncorrelated dataset having a similar correlation coefficient.

<table>
<thead>
<tr>
<th>correlation</th>
<th>$r_P$</th>
<th>$p_P[%]$</th>
<th>$\tau_K$</th>
<th>$p_K[%]$</th>
<th>$\rho_S$</th>
<th>$p_S[%]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c$ - alt.</td>
<td>-0.53</td>
<td>4.3</td>
<td>-0.33</td>
<td>8.0</td>
<td>-0.41</td>
<td>12.6</td>
</tr>
<tr>
<td>PWV - alt.</td>
<td>-0.52</td>
<td>4.4</td>
<td>-0.39</td>
<td>4.2</td>
<td>-0.59</td>
<td>2.0</td>
</tr>
<tr>
<td>$u_{200}$ - lat.</td>
<td>0.64</td>
<td>1.8</td>
<td>0.19</td>
<td>35.7</td>
<td>0.31</td>
<td>30.6</td>
</tr>
</tbody>
</table>
3.3. Results & Discussion

Figure 3.11: Correlation of yearly averages of 200 hPa wind speed and latitude. Values of the Pearson correlation coefficient $r_p$, the Kendall correlation coefficient $\tau_k$ and the Spearman correlation coefficient $\rho_s$ are shown. Mid-latitude sites have higher 200 hPa wind speeds due to the proximity of the subtropical jet stream. The high-latitude sites Dome A and Dome C (colored light gray) were excluded when computing the correlation coefficients.
3.4 Long-term trends

In order to quantify possible impacts of climate change on the quantities studied, their time evolution was examined. For each parameter, yearly averages were computed and ordered by rank. A Wilcoxon-Mann-Whitney (WMW) rank sum test was then performed for each parameter and each site (Mann & Whitney 1947). In the WMW test, the sample of annual mean values was ordered and the rank of each value was determined. The sample was then divided into two equal subsamples, containing values from before and after 1980 (samples 1 and 2 respectively). The vertical wind velocity data are available only for the years 1989 – 2009, so those samples were split at 1999.

The test statistic $U_2 = R_2 - n_2(n_2 + 1)/2$ was then computed. Here $R_2$ is the sum of the ranks of the annual means in the second (later) sample and $n_2$ is the number of values in that sample. The null hypothesis $H_0$ is that it is equally likely that a randomly-selected value from

Figure 3.12: The yearly averages for the wind speed at 200 hPa $u_{200}$ have been fitted with a linear regression model. In the plot the data for La Palma are shown. The slope of the fitted line is $-6.75 \cdot 10^{-2}$ m/(s year). The linear regression model yields a type I error $\alpha = 0.56\%$ for the null hypothesis $H_0$ of a vanishing slope ($m=0$). Results for all sites can be found in Table 3.5.

$\alpha$
3.4. Long-term trends

Figure 3.13: 5-year averages of the 200-hPa wind speed $u_{200}$. 
### 3.4. Long-term trends

Table 3.4: The statistic $x$ for the Wilcoxon-Mann-Whitney test, applied to 45 years of ERA-40 data. Values of $|x| > 2.58$ indicate that the null hypothesis of no long-term trend is rejected with 99% confidence and are displayed in boldface. Positive values of $x$ correspond to a long-term increase in the parameter and negative values indicate a decrease.

<table>
<thead>
<tr>
<th>Site</th>
<th>$f_c$</th>
<th>$u_{200}$</th>
<th>$PWV$</th>
<th>$v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ali</td>
<td>−1.74</td>
<td>3.38</td>
<td>−3.45</td>
<td>−0.23</td>
</tr>
<tr>
<td>Ascension</td>
<td>1.01</td>
<td>2.54</td>
<td>4.32</td>
<td>1.59</td>
</tr>
<tr>
<td>C. Pachon</td>
<td>3.97</td>
<td>−0.23</td>
<td>1.83</td>
<td>−1.06</td>
</tr>
<tr>
<td>C. Paranal</td>
<td>−0.92</td>
<td>−1.74</td>
<td>0.77</td>
<td>−0.83</td>
</tr>
<tr>
<td>Chajnantor</td>
<td>−1.92</td>
<td>−2.46</td>
<td>−3.75</td>
<td>−2.12</td>
</tr>
<tr>
<td>DAG</td>
<td>−1.78</td>
<td>0.14</td>
<td>−0.35</td>
<td>1.66</td>
</tr>
<tr>
<td>Devasthal</td>
<td>−2.84</td>
<td>3.08</td>
<td>−2.82</td>
<td>−0.23</td>
</tr>
<tr>
<td>Dome A</td>
<td>3.22</td>
<td>0.39</td>
<td>4.37</td>
<td>0.15</td>
</tr>
<tr>
<td>Dome C</td>
<td>5.26</td>
<td>−1.38</td>
<td>4.79</td>
<td>−0.91</td>
</tr>
<tr>
<td>Hanle</td>
<td>−1.83</td>
<td>3.38</td>
<td>−3.38</td>
<td>2.11</td>
</tr>
<tr>
<td>La Palma</td>
<td>2.16</td>
<td>−2.68</td>
<td>0.47</td>
<td>−0.83</td>
</tr>
<tr>
<td>Maidenak</td>
<td>0.39</td>
<td>0.82</td>
<td>3.17</td>
<td>1.13</td>
</tr>
<tr>
<td>Mauna Kea</td>
<td>−1.74</td>
<td>−1.20</td>
<td>−1.90</td>
<td>−0.08</td>
</tr>
<tr>
<td>Mt. Graham</td>
<td>3.05</td>
<td>1.03</td>
<td>2.46</td>
<td>1.59</td>
</tr>
<tr>
<td>Siding Spring</td>
<td>−0.09</td>
<td>2.02</td>
<td>−0.82</td>
<td>0.60</td>
</tr>
</tbody>
</table>

One sample will be greater or lesser than a randomly selected value from the second sample. In other words, the null hypothesis is that there is no systematic difference in the mean values of the two samples. Under the null hypothesis, the parameter

$$x = \frac{2U_2 - n_1n_1}{\sqrt{n_1n_2(n_1 + n_2 + 1)/3}},$$  \hspace{1cm} (3.10)

where $n_1$ and $n_2$ are the sample sizes, has an approximately standard normal distribution. Therefore, if $|x| > 2.58$ (or 3.30), the null hypothesis is rejected with 99% (or 99.9%) probability.

All results for the WMW test are presented in Table 3.4. Parameters that show statistically-significant (at the 99% level) long-term trends are highlighted in boldface. In addition to the WMW test, the one-year averages were analyzed by linear regression. The results of the linear regression can be found in Table 3.5 and an example is shown in Figure 3.12. It can be seen from Tables 3.4 and 3.5 that C. Pachon, Dome A, Dome C and Mt. Graham all show
3.5 Conclusions

Table 3.5: Slopes of linear regression lines for yearly-averages of four parameters. The listed values correspond to the projected change in the mean value of the parameter over a period of 100 years.

<table>
<thead>
<tr>
<th>Site</th>
<th>$f_c$</th>
<th>$u_{200}$ (m s(^{-1}))</th>
<th>PWV (kg m(^{-2}))</th>
<th>$v$ (cm s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ali</td>
<td>-0.041</td>
<td>8.98</td>
<td>-0.57</td>
<td>-0.012</td>
</tr>
<tr>
<td>Ascension</td>
<td>0.110</td>
<td>3.73</td>
<td>4.87</td>
<td>0.047</td>
</tr>
<tr>
<td>C. Pachon</td>
<td>0.160</td>
<td>-1.41</td>
<td>1.59</td>
<td>-0.077</td>
</tr>
<tr>
<td>C. Paranal</td>
<td>-0.020</td>
<td>-6.10</td>
<td>0.07</td>
<td>-0.037</td>
</tr>
<tr>
<td>Chajnantor</td>
<td>-0.027</td>
<td>-6.98</td>
<td>-0.51</td>
<td>-0.099</td>
</tr>
<tr>
<td>DAG</td>
<td>-0.061</td>
<td>0.10</td>
<td>-0.22</td>
<td>0.055</td>
</tr>
<tr>
<td>Devasthal</td>
<td>-0.122</td>
<td>7.81</td>
<td>-1.59</td>
<td>-0.029</td>
</tr>
<tr>
<td>Dome A</td>
<td>0.210</td>
<td>0.01</td>
<td>0.17</td>
<td>0.005</td>
</tr>
<tr>
<td>Dome C</td>
<td>0.439</td>
<td>-1.78</td>
<td>0.31</td>
<td>-0.008</td>
</tr>
<tr>
<td>Hanle</td>
<td>-0.048</td>
<td>8.98</td>
<td>-1.20</td>
<td>0.025</td>
</tr>
<tr>
<td>La Palma</td>
<td>0.061</td>
<td>-6.75</td>
<td>0.45</td>
<td>-0.037</td>
</tr>
<tr>
<td>Maidanak</td>
<td>0.003</td>
<td>1.64</td>
<td>1.53</td>
<td>0.037</td>
</tr>
<tr>
<td>Mauna Kea</td>
<td>-0.084</td>
<td>-4.99</td>
<td>-0.77</td>
<td>-0.008</td>
</tr>
<tr>
<td>Mt. Graham</td>
<td>0.184</td>
<td>0.98</td>
<td>1.30</td>
<td>0.035</td>
</tr>
<tr>
<td>Siding Spring</td>
<td>-0.011</td>
<td>7.30</td>
<td>-0.28</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Significant trends of increasing cloud cover, on the order of 2% per decade (4% for Dome C). In contrast the mean cloud cover at Devasthal is decreasing, at about 1% per decade. The yearly mean values of 200-hPa wind speed are shown in Figure 3.13. Significant trends were found for Ali, Devasthal and Hanle, which all show an increase of about 0.8 m s\(^{-1}\) per decade, and La Palma which shows a decrease of about 0.6 m s\(^{-1}\) per decade. PWV has increased significantly for Ascension Island, Dome A, Dome C and Maidanak. It has declined for Ali, Chajnantor, Devasthal and Hanle. However one should keep in mind that PWV can be affected by long-term oscillatory phenomena such as the Interdecadal Pacific Oscillation [Salinger et al. 2001]. This mainly impacts the Andes and the Himalaya region which might be the cause of the observed changes.

3.5 Conclusions

These data show a high degree of variability, but a number of systematic trends are evident. As might be expected, high, dry sites have the best weather and lowest PWV. For the South-Asian
3.5. Conclusions

sites, the monsoon is a dominant factor, although its impact decreases north of the highest peaks of the Himalayas. A similar phenomenon is seen in the American South-West, to a lesser degree. PWV is heavily influenced by the monsoon, with large variations seen at Devasthal, Hanle, Mt Graham and Ali. The other sites show little seasonal variation, with the exception of Ascension Island and Siding Spring. Despite strong regional effects on weather, site altitude is a primary factor influencing yearly PWV averages. The atmosphere over higher sites contains less water vapour on average.

The 200 hPa wind speed shows interesting patterns. A strong upper-level flow develops in the winter months over the Himalayan region (Devasthal, Hanle and Ali). In the summer it shifts northward and the wind over this region drops to less than 10 m s\(^{-1}\). This suggests that telescopes here equipped with GLAO might achieve very good image quality during the summer months. However, this is partly offset by the monsoon, which increases cloud cover. A similar, but less strong, effect is seen at Mt. Graham, and to a lesser degree at Mauna Kea and La Palma. The Chilean sites exhibit this effect also, with the lowest 200 hPa winds occurring in the southern summer. In contrast, upper-level winds over the polar and equatorial regions are weak year round.

Interesting long-term trends are seen, which likely reflect impacts of climate change. The Antarctic sites in particular show highly-significant increases in cloud cover and PWV over the 45-year period of our data. The increases in cloud cover seen at C. Pachon and Mt. Graham are also significant, but may be more of a regional effect - we do not see a comparable increase at C. Paranal. Chajnantor, Ali and Hanle and Devasthal all show a significant trend of decreasing average PWV, while Ascension Island shows a significant increase. The average upper level winds have been increasing over the South-Asian sites. This may be due to a migration of jet patterns, rather than a systematic increase in wind speeds, as these three sites are close to each other.
Chapter 4

Site testing

When a new site for a future telescope is studied, the cloud cover statistics, the precipitable water vapour and the seeing at the site need to be evaluated. The cloud cover statistics reveal the potential number of nights or hours per year which can be used for observations. The atmospheric transmission in some bands depends on the precipitable water vapour above the site. The higher the altitude of a site the less precipitable water vapour above. For example, the radio telescope ALMA needs a high, dry site to avoid absorption by water molecules. As shown in Chapter 2, the seeing and the other atmospheric parameters for optical turbulence depend on the \( C^2_N \)-profile of the turbulence. This quantity is not stable but evolves with time. For assessing a potential site, detailed seeing statistics need to be measured over some years. For evaluating sites, both coarse-spaced meteorological data or models, like the data presented in the previous chapter and specific data from in-situ site testing campaigns are used. For the three next-generation extremely large telescopes, site testing campaigns have been conducted (Vernin et al. (2011), Schöck et al. (2009), Prieto et al. (2010)). For in-situ site testing campaigns, instruments measuring the seeing directly or instruments measuring \( C^2_N \)-profiles are used. Different models for \( C^2_N \)-profiles have been suggested (Hufnagel (1974), Valley (1980), Tokovinin & Travouillon (2006)). A comparison of different models is shown in Figure 4.1. These models distinguish between ground-layer contributions, planetary boundary layer contributions and free atmosphere contributions to the turbulence profile.

Large-scale meteorological effects (the jet-stream and the local geography) are of importance to the seeing conditions. Ground layer turbulence is mainly caused by irregularities in the topography of the landscape underneath the flowing air stream. If no obstacles are present the wind can flow as a laminar stream. When the laminar stream approaches a mountain ridge, past the ridge, laminar air flow breaks down. This phenomena is important and shown in Figure 4.2 as it explains the outstanding observing conditions on island mountains (e.g. Mauna Kea on Hawaii) or on the first high peak on a mountain range by the sea (e.g. Paranal in Chile). The contribution from ground-layer turbulence is significant for the integrated \( C^2_N \)-profile.
In the first part of this chapter, some of these instruments are reviewed. In the second part of the chapter, two scintillometers used for site testing campaigns in Tibet and Columbia are discussed and theoretical background for their use is explained.

4.1 Site testing instruments

4.1.1 Differential image motion monitor

Light from a single object in the sky travelling to a twin aperture, with apertures only a few aperture-diameters apart, will have differently deformed wavefronts. The wavefronts have
different tilt terms, resulting in different image motion on the two apertures. In order to avoid tracking errors which two separate telescope mounts would cause, an approach measuring the differential image motion with a twin aperture is not sensitive to tracking errors (Sarazin & Roddier 1990). A schematic can be seen in Figure 4.3. The covariance of the angle of arrival is related to the phase covariance from which the phase structure function and Fried parameter can be inferred. With the Fried parameter, the value for the seeing can be calculated. These differential image motion monitors (DIMM) were introduced as part of the site testing campaign for the VLT (Sarazin 1986b,a). They are well-suited for providing seeing statistics and are essential in any site testing campaign. Nonetheless, unlike other instruments for site testing, DIMMs do not provide height-resolved $C_N^2$-profiles, just integrated seeing values.
Figure 4.3: Principle of a differential image motion monitor from Tokovinin (2002). ©The Astronomical Society of the Pacific. Reproduced with permission. All rights reserved. [https://iopscience.iop.org/article/10.1086/342683/pdf](https://iopscience.iop.org/article/10.1086/342683/pdf)
4.1.2 Multi-aperture scintillation sensor

The multi-aperture scintillation sensor (MASS) uses the light from a single bright star (Kornilov et al. 2003). The MASS has multiple photomultipliers measuring the intensity of the star light. Scintillation originating from turbulence at different altitudes in the atmosphere induces variations of relative flux fluctuations for different photomultiplier pairs. The variance of the difference of the relative flux fluctuations for a pair of photomultipliers yields the strength of the scintillation. To restore the profile, the turbulence profile is represented as a combination of a finite number of turbulence layers at specific altitudes. The number of turbulence layers can not exceed the number of combinations for pairs of photomultipliers possible. For each combination of photomultiplier pairs, an altitude-dependant weighting function is introduced. The theory predicts that the scintillation indices are a linear combination of the turbulence integrals for the different layers, multiplied by the corresponding weight functions. The layer intensities, which will finally yield the turbulence profile, can be found by solving the system of linear equations. The system of linear equations is solved numerically.

4.1.3 Scintillation detection and ranging

The scintillation detection and ranging (SCIDAR) technique uses a binary star system and one imaging aperture. For the double-stars, a turbulent layer produces the same scintillation pattern, at a separation on the ground. The separation depends on the product of layer altitude and angular separation of the binary system (Avila et al. 1997). The autocovariance of the pupil image is calculated. Since turbulent layers introduce similar scintillation patterns for both PSFs of the stars, the autocovariance peaks at distances corresponding to the heights of turbulent layers. The height of each peak indicates the strength of the turbulence in this layer.

Since the scintillation variance is proportional to $h^{5/6}$, classical SCIDARs are blind to turbulence in the ground layer or the planetary boundary layer. Generalized SCIDARs have an optical setup added or use a technique of moving the detector along the optical axis of the telescope, which enable measurements of the scintillation in the lower atmosphere. For generalized SCIDARs the pupil image and the image plane do not coincide. The image plane corresponds to a conjugate altitude at which the scintillation is analyzed (Fuchs et al. 1998). The height of the conjugate altitude depends on the offset between image plane and pupil plane. The layout of a SCIDAR can be seen in Figure 4.4.
4.1. Site testing instruments

Figure 4.4: Principle of a SCIDAR (Fuchs et al. 1998). The scintillation of a single layer observed at $\Delta z + z_0$ is generated by turbulence at $\Delta h + h_0$. $\Delta h$ is given by $\Delta h = G^2 \Delta z$. ©The Astronomical Society of the Pacific. Reproduced with permission. All rights reserved. [Link to PDF]

4.1.4 Slope detection and ranging

Slope detection and ranging (SLODAR) instruments use a technique similar to the one used by SCIDARs, for measuring $C_N^2$-profiles. A binary system is observed through a telescope with a wavefront sensor. The Shack-Hartmann wave-front sensor measures the local gradients in phase aberration. The angular separation between the stars in the binary system should be large enough, to prevent the PSFs of the binary stars to overlap on the detector. Exposure times need to be shorter than the crossing time of turbulent layers over the subaperture (Wilson 2002). For each subaperture the wave-front slope is calculated. By subtracting the overall slope affecting all subapertures, telescope tracking errors can be accounted for. The ensemble average over the subapertures for the cross-correlation of the slopes of the binary stars is calculated. Response functions can be calculated by the ensemble average of the auto-correlation of the slopes in different subapertures for one single star. The $C_N^2$-profile can then be found by deconvolving the ensemble-averaged cross-correlations with the response functions.

The altitude resolution for this technique is proportional to angular separation of the binary system and number of subapertures. The maximum altitude for the profiles is inversely proportional to the angular separation i.e. binary systems with large angular separation yield well-resolved profiles, but just up to a low altitude.
4.1.5 Sound detection and ranging

Sound detection and ranging (SODAR) is a well-established technique to sense the lower atmosphere. SODARs use short acoustic pulses sent into the atmosphere, which are backscattered from temperature inhomogeneities or the boundaries between layers of changing wind velocity. From the fluctuations in the backscattered signal, the temperature structure constant and the wind structure constant can be found (Neff & Coulter 1986). From the time of flight measurement, the altitude can be inferred. The cells of homogenous temperature normally are of the size of the Kolmogorov inner scale. Temperature and wind structure constants can be converted into the refractive index structure constant. Typically, SODARs transmit 2 to 300 W at frequencies of 1000 to 4500 Hz and pulse lengths are between 50 and 300 ms (Crescenti 1997). With SODARs the first 1000 m of the atmosphere can be sensed.

4.1.6 Solar and lunar scintillometers

Solar and lunar scintillometers use extended sources, observed by an array of photodiodes for turbulence characterization. Scintillation of light from an extended object is found to be correlated with seeing (Beckers 1993). For daytime turbulence profiling, instruments observing the Sun can be used, and for nighttime instruments observing the Moon are used. The light received by the photodiodes propagate through cones from the extended object to the detector. The cones for two detectors start to overlap at an altitude related to the spatial distance between the two detectors. Thus, the light arriving at the detector has travelled through a part with correlated turbulence (overlapping cone) and through a part of uncorrelated turbulence (non-overlapping cone). From cross-correlating the intensity signals the strength of turbulence can be found. The research group at UBC, led by Paul Hickson, built five different scintillometers. These instruments were used for nighttime turbulence profiling in the Canadian Arctic (Hickson et al. 2013) and to study the contribution of dome seeing at the Canada-France-Hawaii Telescope (Pfrommer & Hickson 2015). Scintillometers yield well-resolved $C_N^2$-profiles of the lowest atmosphere. Scintillation in the upper atmosphere casts larger ‘shadows’ on the ground. Since these larger shadows will be cast on all diodes of the instrument, the covariance of all the signals will be affected by it. However scintillometers are less sensitive to high-altitude turbulence due to the effect of the outer scale $L_0$. 
4.2 Theory behind scintillometers

Lunar (and solar) scintillometers use extended sources for measuring ground-layer optical turbulence profiles (Beckers 1993, Hickson & Lanzetta 2004). A detector array perpendicular to the line of sight, measures the intensity fluctuations of the incoming light, see Figure 4.5. This section will focus on the theory behind scintillometers. The derivation for the calculation of turbulence profiles from measured data in this section follows the derivations in Roddier (1981). First we will focus on light fluctuations from a point-source induced by a single thin turbulent layer. The calculation will be generalized to an atmosphere of continuous turbulence. Later the approach will be expanded to extended light sources.

4.2. Theory behind scintillometers

The light from a distant point-source arrives as plane parallel waves at the top of the atmosphere. As it propagates through the atmosphere, phase fluctuations are induced by refractive index fluctuations. The complex amplitude of the electromagnetic wave at distance $z$ from the instrument can be written as

$$\Phi(x, z) = \exp \left( \chi(x, z) + i\phi(x, z) \right), \quad (4.1)$$

where $x$ is a two-dimensional coordinate vector in a plane perpendicular to the direction of $z$, $\chi$ is the log amplitude and $\phi$ is the log phase of the wave. A single turbulent layer will introduce phase fluctuations of $\delta\phi$, resulting in a change of the amplitude

$$\delta \ln [\Phi(x, z)] = i\delta\phi(x, z). \quad (4.2)$$

To obtain the radiation field in the plane perpendicular to the line-of-sight at the ground, the phase shift is propagated through the atmosphere using Fresnel diffraction. The fluctuation in the radiation field at the ground is the convolution of the fluctuation at the height of the turbulent layer with the impulse response function of free space. With the Fresnel approximation, the fluctuation in the radiation field at the ground can be written as

$$\delta\Phi(x, 0) = \delta\Phi(x, z) \ast \frac{1}{\lambda z} \exp \left( i\pi \frac{x^2}{\lambda z} \right). \quad (4.3)$$

By combining Equations 4.2 & 4.3 the fluctuation in the radiation field at the ground becomes

$$\delta \ln \Phi(x, 0) = \frac{\Phi(x, z)}{\Phi(x, 0)} \delta\phi(x, z) \ast \frac{1}{\lambda z} \exp \left( i\pi \frac{x^2}{\lambda z} \right). \quad (4.4)$$

As one can assume the fluctuations are small, the radiation field in the turbulent layer and at the detector are similar, resulting in their fraction to be $\approx 1$. The sum of log amplitude and phase fluctuations at the detector then can be written as

$$\delta\chi(x, 0) + i\delta\phi(x, 0) = \delta\phi(x, z) \ast \frac{1}{\lambda z} \exp \left( i\pi \frac{x^2}{\lambda z} \right). \quad (4.5)$$

In other words, if the fluctuation is small, the resulting fluctuation at ground layer is equal to the phase fluctuation at the altitude $z$ propagated to the ground by the Fresnel approximation. Log amplitude and phase fluctuations can be found by comparing real and imaginary parts in the above equation.
4.2. Theory behind scintillometers

\[ \delta \chi(x, 0) = \delta \phi(x, z) * \frac{1}{\lambda z} \cos \left( \frac{\pi x^2}{\lambda z} \right), \quad (4.6) \]

\[ \delta \phi(x, 0) = \delta \phi(x, z) * \frac{1}{\lambda z} \sin \left( \frac{\pi x^2}{\lambda z} \right). \quad (4.7) \]

The fluctuations in log amplitude and phase are characterized by their power spectra

\[ W_{\chi}(f, z) = \int B_{\chi}(r, z) \exp \left( -2\pi i r \cdot f \right) dr, \quad (4.8) \]

\[ W_{\phi}(f, z) = \int B_{\phi}(r, z) \exp \left( -2\pi i r \cdot f \right) dr, \quad (4.9) \]

where \( r \) is a spatial separation in the detector plane and \( f \) is the conjugate spatial frequency. The spatial covariances of log amplitude and phase are defined by

\[ B_{\chi}(r, z) \equiv \langle \chi(x, z) \chi(x + r, z) \rangle \quad (4.10) \]

\[ B_{\phi}(r, z) \equiv \langle \phi(x, z) \phi(x + r, z) \rangle \quad (4.11) \]

and are averaged in the detector plane. The power spectra are the Fourier transforms of the covariances by the Wiener-Khinchin theorem. Since the instrument sits at ground level, the contribution of a thin turbulent layer to the power spectrum at the ground, needs to be determined. The contribution is given by substituting Equations \( 4.6, 4.7, 4.10 \) & \( 4.11 \) into the expressions for the power spectra (Eq. \( 4.8 \) & \( 4.9 \)), evaluating the Fourier integrals and taking the differentials of the power spectra. The differentials of the power spectra at ground level are

\[ \delta W_{\chi}(f, 0) = \delta W_{\phi}(f, z) \sin^2(\pi \lambda zf^2), \quad (4.12) \]

\[ \delta W_{\phi}(f, 0) = \delta W_{\phi}(f, z) \cos^2(\pi \lambda zf^2). \quad (4.13) \]

The differential power-spectrum \( \delta W_{\phi}(f, z) \) at altitude \( z \) was derived before for Kolmogorov turbulence in Equation \( 2.18 \). It is dependent on the \( C_N^2 \)-profile and can be written in terms of the spatial frequency as

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4.2. Theory behind scintillometers

\[ \delta W_\phi(f, z) = 0.38 \sec \gamma \lambda^{-2} f^{-11/3} C_N^2(h) \delta h . \] (4.14)

The integrated power spectra at ground level can be found by an integration of Equations 4.12 & 4.13 over altitude

\[ W_\chi(f, 0) = 0.38 \sec \gamma \lambda^{-2} f^{-11/3} \int_0^\infty C_N^2(h) \sin^2(\pi \lambda f^{-2} h \sec \gamma) dh , \] (4.15)

\[ W_\phi(f, 0) = 0.38 \sec \gamma \lambda^{-2} f^{-11/3} \int_0^\infty C_N^2(h) \cos^2(\pi \lambda f^{-2} h \sec \gamma) dh . \] (4.16)

The equations above relate the power spectra to the \( C_N^2 \)-profile for Kolmogorov turbulence. We are interested in the relation between \( B(f, 0) \) and \( C_N^2(h) \), since intensity fluctuations are measured by the scintillometer. In fact, the scintillometer measures the covariance of intensity fluctuations for diode pairs \( B_I(r, 0) \) which is four times \( B_\chi(r, 0) \),

\[ B_I(r, 0) = 4B_\chi(r, 0) . \] (4.17)

\( B_\chi(r, 0) \) is obtained by the Fourier transform of the power spectrum in Equation 4.15 and the substitution \( \kappa = 2\pi f \). So far the derivation assumed a point-like source of light and a Kolmogorov power spectrum. To introduce the effects of an extended source, a finite detector size, the assumption of a von Karman power spectrum and diffraction, the power spectrum is multiplied by filter functions, denoted by \( F \). The intensity covariance function accounting for these effects is calculated by

\[ B_\chi(r, z) = 2\pi \int_0^\infty z^2 dz \int_0^\infty \kappa^4 W_\phi(\kappa, z) F_L(\kappa) F_k(\kappa, z) F_\Omega(z\kappa) F_D(\kappa) e^{i\kappa r} d^2 \kappa . \] (4.18)

The filter function \( F_L \) for introducing the modification which transforms the Kolmogorov power spectrum to a von Karman power spectrum, according to Equations 2.10 & 2.11 is given by

\[ F_L(\kappa) = \left(1 + \frac{\kappa_0}{\kappa}\right)^{-11/6} . \] (4.19)

The filter function accounting for diffraction is given by

\[ F_k(\kappa, z) = \text{sinc}^2 \left(z \kappa^2 / 2\pi k\right) . \] (4.20)
4.2. Theory behind scintillometers

The scintillometer use the Sun or the Moon, which are extended objects as light sources. The Moon has changing phases with different intensities which need to be accounted for by the filter function $F_\Omega$. The intensity of the radiation from the Moon for a Lunar phase $\alpha$ is given by the Lommel-Seeliger law (Seeliger 1884)

\[ I(\mu, \mu_0, \alpha) = \frac{2 I_0 f(\alpha) \mu_0}{\mu + \mu_0} \, . \] (4.21)

$I_0$ is the intensity of the full moon, $\alpha$ is the angle between incident and scattered radiation, hence $\alpha = 0$ for full moon and the normalized phase function becomes $f(0) = 1$. $\mu_0$ is the cosine of the angle of incidence with respect to the scattering surface and $\mu$ is the cosine of the angle of reflection with respect to the scattering surface. The scattering surface is the surface of the Moon. The intensity of the Moon depends only on the longitude seen from Earth $\Phi$ of the point on the lunar surface and the solar phase angle $\alpha$. The intensity can be written as

\[ I(\Phi, \alpha) = \frac{2 I_0 f(\alpha)}{1 + \cos \Phi - \cos(\Phi - \alpha)} \, . \] (4.22)

The filter function $F_\Omega$ for the finite beam size is calculated by the square of the integration of the intensity over the entire solid angle

\[ F_\Omega(z\kappa) = \left| \int I(\theta)e^{-iz\kappa \theta} d\Omega \right|^2 \, . \] (4.23)

For the case of the Solar scintillometer $\alpha$ can be assumed to be 0. The finite detector size is accounted for by $F_D$, which is the modulus of the integration of the detector response $R$ over the detector area and normalized to unity

\[ F_D(\kappa) = \left| \int R(x)e^{-i\kappa \cdot x} dx \right|^2 \, . \] (4.24)

The relationship between measured covariances $B_I(r, 0)$ and $C_N^2$ then can be established by

\[ B_I(r, 0) = 0.38 \int_0^\infty C_N^2(h) K(h, r) dh \, . \] (4.25)

where the kernel $K(h, r)$ is given by
4.2. Theory behind scintillometers

Figure 4.6: Response functions for the Arctic Turbulence Profiler (ATP). The different lines are the response functions for the 15 different baselines. The image was provided by P. Hickson.

\[
K(h, r) = \frac{\Gamma(8/3) \sin(\pi/3)}{2\pi} z^2 \int_0^\infty \kappa^{1/3} F_L(\kappa) F_k(\kappa, z) F_\Omega(z\kappa) F_D(\kappa) e^{i\kappa r} d^2 \kappa .
\] (4.26)

The kernel is also called the ’response function’. The response functions comprise the effects of diffraction, an extended light source, finite detector size and atmospheric outer scale. The contributions are calculated in frequency space and their product is Fourier-transformed. For the analysis, response functions for parameter sets of lunar phases and atmospheric outer scale are precalculated. Examples of response functions can be seen in Figure 4.6. Equation 4.25 is a Fredholm equation of first order, \(B_I(r, 0)\) and the kernel \(K(h, r)\) are known. Solving for \(C_N^2(h)\) in this equation is complicated and carried out numerically. The numerical method was provided by P. Hickson and will be presented in the next subsection.
4.2. Theory behind scintillometers

4.2.1 Numerical method to obtain the turbulence profile

The scintillometer measures intensity variations in different photodiodes. The covariance for different diode pairs can then be calculated. Equation 4.25 yields the relation between the turbulence profile and the calculated covariances. The Fredholm integral equation can be solved numerically. P. Hickson wrote a python program for solving for the $C_n^2$-profile. This program uses a Metropolis Hastings Markov-Chain Monte Carlo algorithm. As an initial guess for the turbulence profile a Hufnagel-Valley Boundary model (Ulrich 1988) is used

$$C_n^2 = c_1 \exp(-h/h_0) + c_2 \exp(a/a_0) + c_3 a^{10} \exp(-a) \ ,$$  

(4.27)

where $h$ is the altitude above the site, $a$ is the altitude from sea level and $c_1$, $c_2$, $c_3$, $h_0$ & $a_0$ are model parameters which need to be determined. The parameters can be written as components of the model parameter vector $\mathbf{c}$.

For determining the turbulence profile a Bayesian approach is used. The $C_n^2$-profile is retrieved by maximizing the Bayesian posterior probability. The posterior probability is given by

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

(4.28)

where $P(M)$ is the prior probability of the model, and $P(D|M)$ is the likelihood function of obtaining the data $D$ from the model $M$. In the case of the scintillometer, the measured data are the covariances $B_{ik}$ of the intensities in diodes $i$ and $k$. The covariance matrix can then be calculated (Hickson et al. 2010b)

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

(4.29)

We chose the integration time $\tau$ to be 2 min. The notation of the covariance matrix can be simplified. The covariances are ordered by physical baseline length and are written in a vector $\mathbf{B}$. The index $\alpha$ of the components of the vector, runs from $\alpha = 1$ to $n(n-1)/2$, for a number of photodiodes $n$. Then the notation of the covariance matrix transforms to $C_{\alpha\beta} = \text{Cov}(B_\alpha B_\beta)$. The Bayesian likelihood function can then be calculated (Hickson et al. 2010b)

$$P(\mathbf{B}, \mathbf{c}) = \exp \left[ -\frac{1}{2} \sum_{\alpha,\beta=1}^{n(n-1)/2} \left( B_\alpha - \hat{B}_\alpha(\mathbf{c}) \right) C_{\alpha\beta}^{-1} \left( B_\beta - \hat{B}_\beta(\mathbf{c}) \right) \right] ,$$  

(4.30)
where $\hat{B}(c)$ is the calculated covariance vector from Equation 4.25 for model parameters $c$. The components of $c$ are assumed to have a log-normal distribution. The prior model probability from Equation 4.28 can then be written as

$$P(c) = \exp \left( -\sum_r \frac{(\ln c_r - m_r)^2}{2\sigma_r^2} \right), \quad (4.31)$$

where $c_r$ is a model parameter, thus it is a component of $c$. $m_r$ is the mean of $\ln c_r$ and $\sigma_r$ its standard deviation. The model components for the $C_N^2$-profile are found from the maximum posterior probability obtained in the Markov-Chain Monte Carlo process. In the model, the Hufnagel-Valley boundary model for the $C_N^2$-profile, the log-normal distribution for the values of $C_N^2$ and the non-negativity of $C_N^2$ are prior conditions. The assumption of a log-normal distribution for $C_N^2$ can be inferred, since the Fried parameter $r_0$ and $r_{3/5}$ have log-normal distributions. The turbulence integral is proportional to $r_0^{-3/5}$, hence it must have a log-normal distribution. The turbulence integral is obtained by an integration over the $C_N^2$-profile. A sum or integration which has a log-normal distribution can be obtained by summands having log-normal distributions (Churnside & Clifford 1987).

4.3 Nighttime turbulence measurements at Ali Observatory, China

The theory for scintillometers and first prototypes were developed fifteen to twenty years ago. Starting in 2001, the group of P. Hickson, with the help of the UBC machine shop, designed and built five scintillometers. The scintillometers were used for site characterization for different site testing campaigns. After the testing campaigns had ended the instruments were no longer in use and stored. Two of the instruments, the Arctic Turbulence Profiler (ATP) and the Portable Turbulence Profiler (PTP) have recently been reemployed. The ATP was sent to Ali Observatory in western Tibet for nighttime turbulence profiling, while the PTP was equipped for daytime turbulence profiling using the Sun and brought to Colombia. In this section the setup of the ATP at Ali will be described and preliminary results will be shown. In the next section the setup of the PTP and preliminary results from Colombia will be presented. For the ATP, I was responsible for the assembling and testing of the ATP in the lab at UBC and was part of the team which installed the scintillometer at Ali. For the PTP, I was responsible for the testing of the device, explained the usage to our collaborators in Colombia and took the
initial measurements on-site.

The ATP was originally designed and built for operation in the high arctic at PEARL research station on Ellesmere Island. Results have been published in Hickson et al. (2010a) and Hickson et al. (2013). The ATP consists of six rings positioned at different positions. The axis is aligned along the Earth’s axis, except in the case of the arctic site, at +80°N latitude, where it was erected vertically. Each ring is equipped with eight photodiodes, which have a field of view of approximately 36° x 22°. Since the diodes are arranged in a ring-like shape, when the Moon is visible on sky, the Moon is in the field of view on one diode on each ring. Due to the Earth’s rotation, the Moon moves on sky, and photodiodes on the rings are synchronously turned on and off in accordance. In this way the Moon can be continuously monitored. The instrument has no moving parts, which could freeze in harsh weather conditions in the Arctic, or on high-altitude mountain tops. In front of the photodiodes there are optical filters passing light at wavelength greater than 665 nm. The optical filters were installed to block night-sky and auroral emission. The detector assembly is sealed by optical windows, protecting the photodiodes from outside weather and humidity, and can be heated. However, for the operations at Ali Observatory heating is not needed, since weather conditions are dry and the windows are not affected by ice.

In each ring there is an electronic ringboard. The signal of a photodiode is amplified by a low-noise field-effect transistor (FET) amplifier with a 100 MΩ feedback resistor. On the ring-board there is a 8-channel multiplexer, selecting the channel of the illuminated diode. The amplifiers connected to the non-illuminated photodiodes are turned off. After the multiplexer the signal is split into a DC-component and an AC-component. The DC-component is selected by a low-gain channel and the AC-component by a high-gain channel, which uses a 5-pole analog Bessel filter, limiting the bandwidth to 0.05-122 Hz. The analog signal is converted by a digitizer at 800 samples per second, employing 16-bit resolution.

The bottom part of the ATP hosts a TS-7600 single-board computer with a TS-linux operating system. The computer can be accessed through an ethernet interface. A control program is running continuously, calculating the position of the Moon and the Sun. Data acquisition is carried out on the appropriate photodiodes when the Moon is 16° above the horizon and the Sun is 9° below it. The data are stored on a solid-state flash memory.
4.3. Nighttime turbulence measurements at Ali Observatory, China

Ali Observatory is located at 32.30° N, 80.05° E in the Ngari Prefecture in western Tibet. Site A of the observatory lies on a mountain ridge at 5100 m, extending to the East and West. The mountain ridge is located north of the Himalayan main ridge on the Tibetan plateau (see Figure 4.7). To the south a wide valley is separating the mountain ridge from the first mountains of the Himalayan main ridge, reaching heights exceeding 6000 m. To the north of Ali, the plateau is more open with sporadic mountains at lower altitude. Atmospheric conditions at Ali provide a dry high-altitude climate, guaranteeing low water-vapour contamination of the atmosphere. The site is under development for astronomy. At the moment, Site A is equipped with a 60-cm telescope. Two other nearby sites are being developed, along the ridge to the east at 5200 m Site B, and on the peak (5400 m) of the ridge, Site C. At present neither Site B nor Site C have been supplied with power and an internet connection, which are needed for remotely operating the ATP. The ATP installed at Site A could be relocated to one of the other sites in the future.

Figure 4.7: The image shows Ali Observatory Site A and Site B on the left viewed from the road to the peak of the ridge, where Site C is being developed. The ATP was installed at Site A. The image was provided by P. Hickson.

4.3.1 Installation of the scintillometer

Because the scintillometer had not been in use for several years, the electronic ring boards required testing and repair with the help of the UBC electronic shop. Faulty cable connectors
were found to have caused some of the window heaters in the ring boards to fail and were replaced with new ones. The instrument had to be set-up pointing to the celestial north pole. A stand was designed to hold the ATP in position. With Ali being located at 32.30° N, the stand was designed to provide an inclination of approximately 30° for the tube. The stand was built by the UBC mechanic shop and the setup was tested in the lab. The instrument was assembled and tested at UBC and shipped to Ali in one-piece, since there were no facilities for this work at the observatory. The stand was assembled at Ali. One difficult task was the orientation of the stand. The stand had to point to the true north. A compass, pointing to magnetic north would not have been reliable enough for the alignment. The direction of true north was determined by the shadow of a perpendicular hanging-plumb at local noon. Once the stand was aligned it was bolted on to a concrete equipment pad. The instrument was then inserted and fixed to the stand, and connected to the power grid. Network addresses for the Ali network were assigned to the computer of the ATP. The alignment of the stand and the finished setup of the ATP can be seen in Figure 4.8.
4.3. Nighttime turbulence measurements at Ali Observatory, China

Figure 4.8: Image of the ATP installed at Ali Observatory (above). Alignment of the stand using a hanging plumb (below).

Figure 4.8: Image of the ATP installed at Ali Observatory (above). Alignment of the stand using a hanging plumb (below).
Preliminary seeing results for two nights are shown in Figure 4.9. The instrument has been collecting data since May 2018, which by the time of this writing has not all been processed. The preliminary results show a ground layer seeing contribution of below 0.3 arcsec for a night with good conditions from a height 10 m above ground. For a night with poor seeing conditions the ground layer seeing reaches 0.5-0.6 arcsec. The ground layer seeing contribution above 200 m is similar for both nights.

Figure 4.9: Preliminary ground-layer seeing results for two nights. The data show the estimated seeing for different heights above the ground. During the night of 27th Oct 2018 seeing was good (left), while for the night of 24th Nov 2018 seeing was poor (right).

4.4 Daytime turbulence profiling in Colombia

In early 2018 we were invited to participate in a site testing campaign for a solar telescope to be built in Colombia. The project is led by a consortium of Colombian universities, Universidad Nacional de Colombia and Universidad Sergio Arboleda. Recently Universidad de los Andes has joined the project. Since the surface around a solar telescope heats up during the day, for daytime observations the contribution of ground-layer turbulence to the seeing is worse than for nighttime. For a potential site the characteristics of the ground-layer turbulence need to be well-studied and understood. Scintillometers are well-suited instruments to resolve ground-layer turbulence and yield $C_N^2$-profiles of the lower atmosphere. This led to equipping the PTP for
The scintillometer consists of eight photodiodes, stacked onto a single beam. The smallest separation is about 10 cm and the longest baseline between two diodes is about 2 m. The signal produced by the photodiodes is amplified by low-noise FET amplifier. The voltages are recorded by an eight-channel, high resolution, fast National Instruments analog-to-digital converter card. The AD-card is employed in a National Instruments computer and is sensitive to voltage changes of $\mu V$. The data acquisition software was developed in Signal Express and is sampling at 1 kHz. Test data taken outside of the UBC Hennings building are shown in Figure 4.10. The data analysis software was provided by P. Hickson and is written in Python. An image of the turbulence profiler can be seen in Figure 4.11.

### 4.4.1 Scientific goals of the solar telescope

The telescope in planning is a single mount one-meter class telescope to be built in Colombia. It will have multiple off-axis magneto-optical filters (MOF’s) and will participate in the solar activity MOF monitor (SAMM) network. The aim of the network is to monitor solar activity and to predict solar flares and coronal mass ejections (CME’s). Solar flares are sudden and local increases in brightness, often occurring in proximity to sun spots. Flares can affect the entire vertical atmosphere around the Sun and result in increased emission of the entire electromagnetic spectrum. The origin of solar flares is not completely understood. Most-accepted theories claim the flares originating from releases of free magnetic energy in active regions around sun spots (Ye et al. 2018). CME’s are events of plasma being ejected from the solar corona. The plasma is carried away in solar winds. The distance travelled by the plasma primarily depends on the release velocity. The plasma can reach the Earth, where it is deflected by the Earth’s magnetic field and penetrates the atmosphere. The origin of CME’s is not completely understood either, but CME’s are believed to originate from instabilities in magnetic fields in the solar atmosphere (Antiochos 1998). CME’s often follow solar flares but can occur as single events, too (Harrison 1995). During the eleven-year cycle of solar activity, flares and CME’s
**Figure 4.10**: Test data taken outside of the UBC Hennings building. The data sequence was taken on 03-09-2018. The signals of the eight channels are shown.

Flares and CME’s, commonly referred to as solar storms, can be a threat for electrical power grids and communication systems. High-energy radiation or charged particles can damage satellites, or reach the Earth’s surface and destroy electrical appliances. In 1859, a solar storm, the Carrington storm (named after the Astronomer Richard Carrington), damaged the telegraph networks in Northern America and Europe. In 1989 a solar storm event caused power outages in parts of Canada. In 2015, air traffic was shut down in Northern Europe, due to communication breakdowns caused by a solar storm. In July 2012, an even stronger solar storm was detected, but was directed away from Earth (Baker et al. 2013). Governments, companies and academic research, in joint efforts, are studying the possible impacts of solar storms (Krausmann et al. 2013). There is a global need for broadcasting systems. The SAMM network will be able to predict solar flares and CME’s. It uses solar telescopes, in different locations on Earth, continuously monitoring the Sun. At the moment there is no telescope in North or South America.
4.4. Daytime turbulence profiling in Colombia

participating in the network, which limits the continuity.

All telescopes in the network employ MOF filters for 3D-scanning of the magnetic field in the Sun’s atmosphere. Spectral lines are studied for sodium, which is located at 600-700 km${^5}$ in the atmosphere and potassium, which occurs at 300-400 km (Stangalini et al. 2018). The sodium is studied at 589.6 nm and the potassium at 769.8 nm. In the future, a filter for calcium, located at an altitude of about 1000 km, will be added. The atmosphere is sampled every five seconds and the filters have a sensitivity to detect changes in the magnetic field of 10 G. The resolution during the observations needs to be about one arcsec. The prediction is based on the behaviour of the horizontal magnetic gradient between sunspots of different polarity (Korsos et al. 2014; Korsós et al. 2015). While the occurrence of sunspots does not yield information for flare prediction, the horizontal magnetic gradient in active regions of the Sun does. Before a flare, the horizontal magnetic gradient at the magnetic neutral line, will show a characteristic behaviour. There will be a steep rise, then a maximum plateau followed by a decrease. The flare will set in after the decrease and can be predicted two to ten hours prior to the initial outbreak. For the intensity of the flare and the maximum horizontal gradient a linear relation has been found (Korsos et al. 2014). Thus, monitoring the horizontal magnetic gradient in active regions predicts solar flares and their intensity. It could be used to warn of oncoming solar flares and possibly following upcoming CME’s, several hours before the eruption.

4.4.2 Results for daytime turbulence profiling in Villa de Leyva, Colombia

The scintillometer was shipped to Colombia in late November 2018. The equipment was tested at the Sergio Arboleda University in Bogota. After the successful testing of the equipment, measurements were made at a site in Villa de Leyva on December 7th. Villa de Leyva is located in a valley at an altitude of 2150 meters. The site is located on a lawn about 50x30 m at the museum for palaeontology. The lawn is surrounded by trees, to the east is a mountainside of a mountain, overlooking the valley by about 500 meters. Between 16:00 and 20:00 (UTC), when an area of 20 degree around the Sun was free of clouds, measurements were carried out. Blocks of data for 2 minutes were taken, and in the interim the pointing towards the Sun was adjusted with the aid of a small telescope attached to the centre of the beam. The results for the seeing are shown in Figure 4.12.

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$^5$ Altitudes given for the solar atmosphere refer to altitudes above the lower boundary of the solar photosphere.
4.5. Concluding remarks on the site testing campaigns

The seeing 10 meters above ground shows strong variations between 1.5 and 3.0 arcsec. From 100 m above ground, the seeing on average is only about one third of the entire ground layer seeing. In the first 100 meters of the atmosphere there is strong turbulence.

4.5 Concluding remarks on the site testing campaigns

At the time of writing of this thesis only preliminary results from the site testing campaigns are available. The ATP has been taking data for one year and the analysis is in progress. Results will be published in the future. It is too early for a final conclusion, but the preliminary results from Ali, show promising conditions for optical and infrared astronomy.

After the first day of measurements, the computer of the PTP failed and is currently being repaired. The data taken are inconclusive, since they were only taken on one day, and site
4.5. Concluding remarks on the site testing campaigns

Figure 4.12: Seeing results from PTP measurements at Villa de Leyva, Colombia. The time between 16:00 UTC and 20:00 UTC corresponds to zenith angles of the Sun between 30° and 50°.

testing campaigns need to run for longer periods to get more conclusive statistics. From the local geography or topology the site in Villa de Leyva might not be the best site for a telescope. However, it is the only site at the moment having the infrastructure for site testing campaigns. Efforts are being made by our Colombian colleagues to find a better site, for example the top of a mountain or an island in a lake, and to provide the infrastructure at the sites for the scintillometer set-up. Our colleagues have been introduced to site testing and scintillometers and have been instructed in using the instrument and reducing data. They are planning on building a copy of the scintillometer to be able to explore multiple sites.
Chapter 5

Sodium laser guide star excitation

Our focus will now turn to sodium LGS. This chapter will highlight the mechanisms involved in LGS excitation. Sodium LGS are elongated columns of neutral sodium in the Earth’s mesosphere, excited by lasers sitting on the ground. The sodium excitation is subject to atomic physics, but since the process takes place in the mesosphere, aspects of physics of the atmosphere affect the sodium atoms. Atmospheric effects decrease the sodium excitation efficiency and thereby decrease LGS return flux. Methods for mitigating these effects are under investigation. One of the studied methods is polarization modulation. Results from a polarization modulation experiment will be presented in the next chapter. First, the excitation by the sodium D2-line and the atmospheric processes or conditions affecting LGS will be introduced in this chapter.

The energy level structure of sodium is rather complex and a full description of it is beyond the scope of this thesis. Monochromatic LGS are excited by and emit light of the sodium D2-line, arising from transitions between the 3S1/2 ground state and 3P3/2 excited state. Due to coupling of the total angular momentum of the electron to the nuclear spin, the energy levels of fine structure are split into hyperfine structure. Energy splitting in the hyperfine structure is small. The 21-cm line of hydrogen is a well-known example of a hyperfine transition. In the hyperfine structure there are two ground states of sodium, having quantum numbers of \( F = 1 \) or \( F = 2 \), with an energy splitting corresponding to 1.772 GHz between these states. The 3P3/2-level is divided into four hyperfine states, with \( F' = 0, 1, 2, 3 \). Note that for the following discussion all excited states will be labeled with an upper prime “’”, while ground states will be labeled without. Sodium atoms in the mesosphere are in a weak magnetic field, the Earth’s magnetic field, resulting in Zeeman splitting of the sodium hyperfine structure. Zeeman splitting adds magnetic substates, ranging from \( m = -F \) to \( m = F \). In total, for each hyperfine state there are \( 2F+1 \) magnetic substates. For weak magnetic fields the Zeeman splitting is proportional to the magnetic field strength. Figure 5.1 shows the energy levels for the sodium D2-line. For strong magnetic fields, the linearity in the energy splitting breaks down.
Chapter 5. Sodium laser guide star excitation

and the Paschen-Back effect sets in. In the presence of a strong magnetic field, total angular momentum and spin are first of all coupled to the magnetic field. The coupling of angular momentum and spin vanishes. Thus, the eigenstates of the Paschen-Back effect are described by a magnetic quantum number for the angular momentum and a magnetic quantum number for the spin. As the Earth’s magnetic field is weak, the Paschen-Back effect will not be further discussed.

Figure 5.1: Hyperfine structure of the sodium D₂-line. Reprinted with permission from Ungar et al. (1989). ©The Optical Society

The lifetime of the $3P_{3/2}$ state is approximately 16 ns. For the excitation of the LGS, both pulsed and CW lasers can be used. For pulse lengths of some hundreds of nanoseconds the sodium atom will be excited multiple times. Thus, optical pumping effects become important for longer pulsed lasers and CW lasers. Most laser formats for LGS are tuned to the sodium D₂a-line and the laser linewidth is a few MHz. The sodium D₂a-line excites transitions from
the $3S_{1/2}$, $F = 2$ ground states. Considering only dipole transitions, the $3P_{3/2}$ $F' = 1$ and $F' = 2$ states can be de-excited into the $3S_{1/2}$, $F = 1$ ground state, which is not excited by the $D_{2a}$-line. Dipole transitions arise from the interaction of the electron’s electric moment and the electromagnetic wave and are described by the first term of the Hamiltonian in time-dependant perturbation theory for the interaction between an electron bound to an atom and the electromagnetic wave. For the excitation of a sodium atom population, over multiple transition cycles, the population will be shifted towards the $3S_{1/2}$, $F = 1$ ground state. This is an unwanted effect, since the number of atoms made available for excitation by the $D_{2a}$-line decreases. By applying about 10-12 % of the laser power to the $D_{2b}$-line, which excites the $3S_{1/2}$, $F = 1$ ground state, an equilibrium in the ratio of atoms in the $3S_{1/2}$, $F = 2$ state and the $3S_{1/2}$, $F = 1$ state is established (Calia et al. 2010). This “repumping” prevents a depopulation of the $3S_{1/2}$, $F = 2$ state and can increase the return of a CW laser by a factor of about 2 under certain conditions. Different transitions between upper and lower states have different cross-sections and transition probabilities. The highest transition probabilities are found for transitions between $|F = 2, m = 2\rangle \rightarrow |F' = 2, m' = 3\rangle$ and for transitions from $|F = 2, m = -2\rangle \rightarrow |F' = 2, m' = -3\rangle$. These transitions can make up to 40% of the LGS return flux, given that circular-polarized light is used for the excitation (Holzlöhner et al. 2010). The high fraction of photons in LGS return flux originating from these transitions is a result of the spatial emission patterns for different polarizations. The emitted photons are circular-polarized. The fraction of photons emitted toward the ground is higher for circular polarization than for linear polarization (Steck 2009). Besides the high transition probability and favourable spatial emission pattern for these transition there is another effect which makes it favourable for LGS excitation. By the fact that atoms are excited to $|F' = 2, m' = 3\rangle$ or $|F' = 2, m' = -3\rangle$, the atoms can only decay to the $3P_{3/2}$ $F=2$ ground state, thus preventing the depopulation of the $3P_{3/2}$ $F=2$ state.

For AO, pulsed lasers and CW lasers are being used. Overall CW lasers yield more LGS return flux (Holzlöhner et al. 2012). For certain laser powers and angles between laser pointing direction and magnetic field, simulations in Rampy et al. (2012) predict long-pulsed lasers to reach 90% of return flux of LGS created by CW lasers of equal power. Because of the high return flux, at the moment most lasers for AO systems in large telescopes are Raman-fiber CW lasers. The lasers employed in AO systems use circular-polarization since it yields higher return

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6The $3P_{3/2}$ $F'' = 0$ is de-excited in the $3S_{1/2}$, $F = 1$, as well, but for dipole transitions, the $D_{2a}$-line, does not excite atoms into that state.
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flux than lasers using linear-polarized light. In order to predict LGS return flux for different laser formats, simulations for the sodium excitation have been developed. There is extensive literature on simulations for LGS return flux. The simulations either use rate equations or solve the optical Bloch equation. Rate equations use the product of the Einstein coefficient and the energy density of the irradiance to calculate the rate of change for the atomic substates. The rate equations yield ensemble averages of the population. Coherent effects in strong electromagnetic fields, e.g. Rabi oscillation, are not accounted for. The most reliable approach for predicting LGS return flux, is the numerical solution of Bloch equations. Bloch equations are a semi-classical approach, since the atom is treated quantum mechanically and the electromagnetic field is treated classically. A Mathematica software package 'LGSBloch' has been developed by S. Rochester and R. Holzlöchner. Bloch equations describe the time evolution of the density matrix. The software package solves optical Bloch equations for the sodium $D_2$-line. The density matrix yields ensemble averages for the occupation of the substates. In case of the sodium $D_2$-line, there are 24 substates. The software keeps track of transitions from spontaneous emission which account for the LGS return flux. Since the electromagnetic field is treated classically in Bloch equations, spontaneous emission needs to be added phenomenologically.

The interaction of magnetic moments and an external magnetic field affects sodium LGS return flux. Since electrons are charged particles, they carry a magnetic moment. Magnetic moments in an external magnetic field precess around the external magnetic field. The effect is well-known from atomic physics and is called Larmor precession. The valence electron of an atom or molecule is subject to Larmor precession and will change its magnetic substate. The Larmor frequency for the precession is given by

$$f_L = \frac{g_F \mu_B B}{\hbar},$$

(5.1)

where $g_F$ is the Landé factor, $\mu_B$ is the Bohr magneton and $B$ is the magnetic field strength. Larmor precession of mesospheric sodium atoms decreases LGS return flux. As discussed above, AO systems use CW lasers producing circular-polarized photons (denoted by $\sigma^+$ for right-handed circular polarization and $\sigma^-$ for left-handed circular polarization). For cycles of multiple excitations of sodium atoms, optical pumping towards the magnetic substates with the highest or the lowest quantum number $m$ will occur. The direction of the pumping depends on the type of circular-polarized light used for excitation. In the absence of an external magnetic field, all atoms would either be shifted to the highest or the lowest magnetic quantum number. This is
a favourable effect, since it would allow for transitions from $F = 2$ to $F' = 3$ with the highest cross-section in the energy scheme, which has been discussed above. Oscillator strengths for transitions of the $D_{2a}$-line by circular-polarized light are shown in Figure 5.2. In the presence of an external magnetic field, the transitions induced by polarized light depend not only on the polarization of the laser, but on the angle between propagation direction and magnetic field. If the polarization plane of the laser does not coincide with the magnetic field direction, a $\sigma^+$-polarized laser will not only induce transitions of $\Delta m = +1$. The transitions being excited with respect to the angle between Poynting vector and magnetic field can be calculated from the Wigner-Eckhardt theorem. It follows, that for different positions on sky, optical pumping will have different strengths, leading to LGS return flux being dependent on the LGS position on-sky (Moussaoui et al. 2009).

A second problem with optical pumping arises from Larmor precession. While the LGS return flux is enhanced by optical pumping with circular-polarized light in the absence of an external magnetic field, Larmor precession will change the magnetic polarization of the atoms in the presence of an external magnetic field. A sodium atom starting in the $|F = 2, m = 2\rangle$ state at
an initial instant of time, will evolve into a superposition of different magnetic quantum numbers \( m \), until after half a Larmor period it reaches the opposite magnetic quantum number \( m = -2 \). Within another half of a Larmor period, it will evolve back into the \( m = 2 \) state. So after a full Larmor period the atom is in the same state as at the start of the period. The effect is shown in Figure 5.3. In a normal AO setup only one type of circular polarization for the laser is used. The transitions with the highest cross-section are a \( \sigma^+ \)-transition for the \( m = 2 \) state and a \( \sigma^- \)-transition for the \( m = -2 \) state. It follows that since Larmor precession is taking place for the sodium atoms in the mesosphere, the atoms can not be excited in the most efficient way during a complete Larmor period, if only one polarization for the irradiance is used. Temporal polarization modulation of the laser should increase the LGS return flux. The modulation switches between \( \sigma^+ \)-polarization and \( \sigma^- \)-polarization. Ideally, one would expect the highest LGS return flux at a modulation of half a Larmor frequency. The method would not only yield a mean for increasing the LGS return flux, but does serve as a remote magnetometer of the Earth’s magnetic field in the mesosphere, since the Larmor frequency can be determined from it. The magnetic field strength follows from Equation 5.1. Studying the mesosphere or processes in it is difficult, as it can not be reached easily by devices used for in-situ testing, like weather balloons. Technical requirements for instruments in this altitude are challenging and projects with in-situ instruments are expensive. This is one reason for processes in the mesosphere still not being completely understood. A technique serving as a remote magnetometer for the mesosphere complements low-altitude and space-based measurements of magnetic fields.

Recoil is another effect decreasing LGS return flux. Over multiple excitation and spontaneous emission cycles, there is a net change in resonant frequency of about 50 kHz per cycle which corresponds to the momentum of the incoming photon. For excitation, the atom absorbs the momentum of the photon. The photons being emitted by spontaneous emission can have any direction. For many emissions the net momentum change from spontaneous emission is therefore 0. The velocity population of the atoms is shifted. The sodium atoms see the laser red-shifted. This phenomena is referred to as spectral hole burning. To overcome the problem, experiments are being conducted with chirped lasers. When high laser power is used saturation sets in. The probability for stimulated emission increases with increasing laser power, while the probability for spontaneous emission does not depend on laser power. Stimulated emission is directed parallel to the direction of the incoming laser light, thus into space and not towards the ground. Saturation refers to laser powers at which the fraction of stimulated emission becomes noticeable and LGS return flux does not continue to increase with increasing laser power. At present
the power of AO lasers is below the saturation threshold.

We carried out an experiment for polarization modulation at the Observatory Roque del Muchachos. A receiver system for the instrument was built at UBC. The preparation and results of the experiment will be presented in the next chapter.
Chapter 6

Results from polarization-modulation magnetometry experiment

Under the lead of F. Pedreros Bustos (Helmholtz Institute Mainz, Johannes Gutenberg University) and in collaboration with the European Southern Observatory, INAF Rome and Rochester Scientific an experiment was designed to study the effects of polarization modulation of a CW laser on LGS. The experiment is ongoing and takes place in different phases. In this thesis the results of the first two phases will be presented. The experiments were carried out at the Observatory Roque de la Muchachos (ORM) on La Palma. The ESO Wendelstein LGS unit and a 14-inch telescope were used. At UBC, P. Hickson and I designed the receiver unit and provided the steering and data acquisition software for the receiver. The frame of the receiver unit was built by the UBC mechanical workshop. The design and building of the receiver will be presented in the next section. The result for the first phase will follow in the subsequent section and the results for the second phase will follow in the next chapter. The first phase of the experiment was aimed to test the feasibility of the setup and show the application as a remote magnetometry technique in the Earth’s mesosphere. In this phase the polarization of the CW laser was not modulated. Instead the laser ran at a low duty cycle for amplitude modulation. In this case the laser was emitting pulses, and was not operated in as a CW laser. The repetition rate of the pulses was modulated. Since only one type of circular polarization was used, one would expect a resonance for the LGS return flux when modulating at the Larmor frequency. For the second phase the laser ran in CW mode and the polarization of the laser was modulated between $\sigma^+$ and $\sigma^-$ polarization. The frequency of the polarization switching was varied.
6.1 Design and construction of a receiver system for the magnetometry experiments

The telescope and the ESO LGS unit are located next to the William Herschel Telescope at ORM. The distance between the small telescope and the laser launch telescope of the LGS unit is about 8 m. The receiver system attached to the backend of the telescope was designed and built at UBC. The receiver system included an optical mount, receiver electronics, software for operating the photomultiplier and data acquisition. The optical mount is attached to a commercial Celestron 14-inch telescope (Celestron Edge HD14). Light falling through the 200 \( \mu m \) pinhole falls onto an optical filter for the sodium D\(_2\)-line. The center frequency of the filter is 589.995 nm and its FWHM is 0.300 nm. The filter blocks light other than the sodium D\(_2\)-line, ensuring that only light from the LGS enters the photomultiplier tube (PMT). The PMT is a Hammatsu H7422 run with a Hammatsu M9012 temperature control and power supply. The PMT transforms the arriving photon into an electrical current. The electrical current is sent to a discriminator (Ortec 9327), which creates 100 ns transistor-transistor logic (TTL) pulses if
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the incoming current exceeds a set threshold. The TTL pulses are sent to the data acquisition system. The receiver unit and an image taken with the finder camera can be seen in Figure 6.1 and in Figure 6.2.

Figure 6.2: Saturn centered on the pinhole, as seen through the finder camera Neximage 5. The ring of Saturn does not fit into the pinhole, it is reflected from the edges. The planet itself is not visible, since its light propagates through the pinhole.

The software controlling and monitoring the PMT was designed in Labview. Its purpose is to control the operation of the PMT. A fan and a Peltier element can also be controlled. Once the temperature of the PMT is low enough for operation, a high-voltage power source can be turned on and the PMT gain can be adjusted. The software for data acquisition was originally developed in Labview. During the first campaign in June and July of 2017, a NI computer was used for the fast time-tagging of the photons. During the campaign the NI computer failed. The time-tagging acquisition system was replaced by a Roithner Laser Technik TTM 8000 connected to a Linux computer. The TTM 8000 is a fast time-tagging module measuring the timing of digital pulses. For the data acquisition, three signals were recorded on the TTM 8000. The acquisition software detects every rising edge of a TTL pulse indicating a photon event and every rising or falling edge of the dither signal in order to document the dither excursion for an incoming photon being positive or negative, and to document the sweep voltage for an incoming photon. The experiments were carried out using a special frequency sweep. A slow linear frequency sweep was combined with a fast frequency switching, called dithering, to
6.1. Design and construction of a receiver system for the magnetometry experiments

frequencies with an offset of $+\delta f$ and $-\delta f$ from the linear sweep. This dithering was necessary to overcome effects of scintillation and changes in the sodium abundance. In a linear sweep these effects would have manipulated the data. The sweep voltage indicates the current frequency in the frequency sweep. A delay was assigned to the dither and sweep signals to account for the roundtrip time of the light from the ground to the sodium layer. As an estimate a sodium centroid altitude of 90 km was used. Figure 6.3 demonstrates the schematic of the input channels for the time-to-digital converter. The experimental setup is described in the following section in more detail.

Figure 6.3: Schematics of the input signals for the time to digital converter. On Channel 1 TTL pulses for photon events arrive. On Channel 2 the fast-oscillating dither signal is recorded. Channel 3 is fed with the sweep voltage, which is related to the frequency of the sweep.
6.2 Remote sensing of geomagnetic fields and atomic collisions in the mesosphere

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Laser excitation of the atomic sodium layer, located between 85 and 100 km altitude in the upper mesosphere, allows astronomers to create artificial light sources, known as LGS, to assist adaptive optics systems (Happer et al., 1994). A laser beam tuned to a wavelength resonant with the $3S_{1/2} \rightarrow 3P_{3/2}$ transition in sodium produces atomic fluorescence that is collected at ground with a telescope for real-time compensation of atmospheric turbulence in astronomical observations. Since the introduction of this technique (Thompson & Gardner, 1987; Humphreys et al., 1991), research has been conducted to optimize laser excitation schemes in order to maximize the flux of photons returned to the ground. This technological progress has also catalyzed new concepts of laser remote sensing of magnetic fields with mesospheric sodium (Higbie et al., 2011). Because of the proximity of the sodium layer to the D and E regions of the ionosphere (between 70 and 120 km altitude) mesospheric magnetometry opens the possibility of mapping local current structures in the dynamo region (Yamazaki & Maute, 2017; Blanc & Richmond, 1980). In addition, the capability of continuously monitoring the geomagnetic field at altitudes of 85-100 km could provide valuable information for modeling the geomagnetic field, detection of oceanic currents (Tyler et al., 2003), and for mapping and identification of large-scale magnetic structures in the upper mantle (Maus et al., 2008).

In a laser magnetometer, atoms are optically polarized and the effects of the interaction of the polarized atoms with magnetic fields are observed (Budker & Romalis, 2007). For instance, optical pumping of sodium with left-hand circularly polarized light produces atomic polarization in the $|F = 2\rangle$ ground state ($F$ is the total angular momentum quantum number), which is continuously depolarized as the angular momentum precesses at the Larmor frequency in the local magnetic field (Auzinsh et al., 2010). If the medium is pumped with light pulses synchronized with the Larmor precession, a high degree of atomic polarization can be obtained and an increase in the fluorescence in the cycling transition can be observed (Bell & Bloom, 1961). The direct measurement of the Larmor frequency ($f_L$) gives the magnetic field $B$ from
where $\gamma$ is the gyromagnetic ratio of ground-state sodium given by $\gamma = 699.812$ kHz G$^{-1}$. This relationship applies to weak magnetic fields where Zeeman splitting of the energy levels depends linearly on the field. Therefore, as proposed in Higbie et al. (2011), pumping the sodium layer with an intensity-modulated laser beam and observing the magneto-optical resonance occurring at the Lamor frequency from the surface of the Earth allows one to remotely detect the magnetic field in the mesosphere. The first observation of a magnetic resonance and remote magnetic field determination in the mesosphere were recently reported in Kane et al. (2018). Here, we demonstrate mesospheric magnetometry with an order-of-magnitude better sensitivity due to a number of factors, including exploiting the narrower magnetic resonance feature. In this work, the observed characteristic spectroscopic features of the resonance curve enable quantitative characterization of collisional processes in the mesosphere.
6.2. Remote sensing of geomagnetic fields and atomic collisions in the mesosphere

Figure 6.4: Experimental arrangement. A laser projector sends an intensity-modulated beam to the mesosphere where it polarizes sodium atoms. Fluorescence is observed with a second telescope and the received photons are recorded, counted and demodulated with a digitizer, a photon counter, and a lock-in amplifier, respectively. The change in fluorescence is measured as the laser modulation frequency is swept around the Larmor frequency driving the acousto-optic modulator (AOM) using a signal generator. The lock-in amplifier provides the reference to dither the intensity-modulation frequency to discriminate atmospheric scintillation noise.

In the following, we describe the details of our experiment to measure the Larmor precision frequency of sodium atoms. We discuss the resonance features, precise measurements possible with our magnetometry method and the collision relaxation rates. In addition to magnetometry,
our observations have yielded quantitative information about collisional processes in the mesosphere, which is important for the optimization of sodium laser guide stars and mesospheric magnetometers.

6.2.1 Results

**Experimental setup.** The experimental setup is depicted in Fig. 6.4. It used the European Southern Observatory Wendelstein Laser Guide Star Unit (ESO WLGSU) installed next to the William Herschel Telescope (WHT) at the Observatorio del Roque de los Muchachos (ORM) in La Palma. The operation of the WLGSU allows modulation of the beam and pointing the transmitter and receiver telescopes at the same target. The setup incorporated a laser projector telescope and a receiver telescope separated by eight meters. The light source consisted of a continuous-wave Raman-fiber-amplified frequency-doubled laser with a maximum output power of 20 W (Calia et al. 2012). The laser was tuned to the vacuum wavelength of 589.158 nm (corresponding to a wavelength of 589.995 nm at atmospheric pressure) arising from the $3S_{1/2} \rightarrow 3P_{3/2}$ transition of sodium (the D$_2$-line); the linewidth of the laser was measured to be $\approx 2$ MHz. The laser system incorporated an AOM (acousto-optic modulator) for on-off amplitude modulation of the beam intensity. The beam polarization was controlled with a set of waveplates following the AOM. The Galilean projector telescope magnified the beam to an output diameter of 30 cm. The receiver consisted of a 40-cm aperture Schmidt-Cassegrain telescope mounted on the WLGSU receiver control unit, equipped with a narrow-band interference filter of 0.30(5) nm bandwidth centered at the sodium D$_2$-line wavelength, a tracking CMOS (complementary metal-oxide-semiconductor) camera and a PMT (photomultiplier tube). A discriminator was used to filter and convert the analog pulses from the PMT into 100 ns TTL (transistor-transistor logic) pulses for the photon counters. The signal was acquired by three independent methods: (a) digitizing and counting the arrival of individual photons (offline mode), (b) directly measuring and averaging the photon-count difference per modulation period (online counter), and (c) directly demodulating the signal from the PMT with a lock-in amplifier.
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Figure 6.5: Fluorescence of mesospheric sodium. A five-second-exposure raw image of the sodium fluorescence spot in the mesosphere along with the star HIP113889 obtained with the CMOS camera of the receiver telescope. The estimated long-term spot size is 3.1 arcsec, which comprises broadening due to atmospheric propagation and focusing error of the receiver telescope. Rayleigh scattering from the laser propagation in lower layers of the atmosphere is visible in the bottom-right corner of the image.

Each observation run consisted of a discrete frequency sweep of the laser intensity modulation around the predicted Larmor frequency. In order to reduce atmospheric scintillation noise, the frequency of the laser intensity modulation at each step of the sweep ($f_{\text{step}}$) was dithered with a square-wave function such that

$$f_{\text{pulse}}(t) = f_{\text{step}} + \delta f \cdot \text{sgn}[\cos(2\pi f_m t)],$$  \hspace{1cm} (6.2)

where $f_{\text{pulse}}(t)$ is the frequency of the laser intensity modulation, $\delta f$ is the excursion of the dither, $f_m$ is the dither frequency and sgn is the sign function. The information of the magneto-optical resonance is therefore contained in the amplitude of the alternating signal which oscillates at $f_m$. When $f_{\text{step}}$ increases and approaches the magneto-optical resonance, a dip (or peak) occurs depending on the polarity of the reference signal used for demodulation. The op-
posite situation occurs when the intensity-modulation frequency exceeds the Larmor frequency along the sweep. Therefore, demodulation produces a peak and a dip separated from each other by $2\delta f$ and centered at $f_L$. The excursion was varied from $\delta f = 8$-45 kHz to find the optimal separation between demodulated peaks, and the dither frequency was fixed at $f_m = 150$ Hz to suppress scintillation noise. Because some of the sodium atoms decay into the dark $F = 1$ ground state (McClelland & Kelley 1985), a fraction of the laser power (12%) was detuned by +1.713 GHz in order to maximize the number of available atoms by pumping them back into the $F = 2$ ground state via the $F' = 2$ excited state. The duty cycle of the laser intensity modulation was varied from 10 to 30%, as a compromise between high return flux and effective optical pumping. Laser polarization was kept circular for all runs in order to prepare the required orientation of the atomic spins along the laser-beam direction. The laser beam pointed in a direction at which the magnetic field vector in the mesosphere was approximately perpendicular to the laser-beam axis, which gives the highest contrast for the magneto-optical resonance. According to the World Magnetic Model (WMM2015) (Chulliat et al. 2015), the declination and inclination of the magnetic field at La Palma are 5.7° West and 39.1° downwards, respectively. Therefore, observations were carried out at an elevation of about 51° in the northern direction. Nevertheless, pointing at higher elevation up to 75° was also explored in order to reduce the airmass contribution to scintillation and the magnetic field uncertainty due to a shorter sodium layer path along the laser beam. From the WMM2015, the estimated magnetic field strength at 92 km altitude is 0.3735 (15) G, corresponding to a predicted Larmor frequency of $\approx 261$ kHz.

The duration of each run depended on the frequency range of the sweep and the integration time for each step. About 10 minutes were necessary to perform a sweep of $\pm 75$ kHz around the Larmor frequency. During five nights of observations from July 2nd to July 6th 2017, there were 51 successful runs. Laser power, duty cycle and excursion parameters were modified from run to run to investigate their effects on the magneto-optical resonance. The average atmospheric seeing was 0.7 arcsec measured at zenith and at 500 nm, as reported by a seeing DIMM collocated at the observatory. Data from the seeing monitor are available online from the website of the Isaac Newton Group of Telescopes (ING). Physical-optics modeling of the mesospheric spot size under these conditions gives an instantaneous FWHM beam diameter of $D_{FWHM} = 36$ cm (0.8 arcsec) for a 30-cm launch telescope at an elevation angle of $\theta_{EL} = 60°$, and average mesospheric irradiance of $I_{meso} = 15$ W m$^{-2}$ for 2-W CW laser output power (because of the
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duty cycle and finite AOM efficiency, 10-20% of the average laser power was delivered to the sky). The spot size in the mesosphere was estimated from a long-exposure image taken with the receiver CMOS camera to be 3.1 arcsec (Fig. 6.5), however, this estimate is subject to the effects of double-pass laser propagation through the atmosphere, beam-wander, and focusing error of the receiver, each of which contribute to broaden the apparent fluorescent spot beyond the instantaneous spot size. Since the spin-precession dynamics occurs on time scales of microseconds, we calculate the irradiance in the mesosphere using the instantaneous beam size obtained from physical-optics (Holzlöhner et al. 2008).

Magneto-optical resonances. Figure 6.6 shows three typical demodulated signals obtained with an online differential counter (Fig. 6.6a), an offline ratio counter (Fig. 6.6b), and a lock-in amplifier (Fig. 6.6c). The online counter reported the real-time difference in the photon counts between two half-periods of the dither signal, averaged over the time of each frequency step (2-3s). The averaged maximum count difference per dither period of 6.7 ms (150 Hz) was only about seven photon counts, when the frequency reached the Larmor frequency. Therefore, the maximum averaged difference between off-resonance and on-resonance is about 1000 counts s\(^{-1}\) as shown in Fig. 6.6a. A higher dither frequency would have rejected scintillation noise better, at the cost of fewer photon counts per dither period. The digitizer recorded all photon counts and the ratio between alternating dither sub-periods was calculated. During post-processing, the phase of the square-wave dither signal could be freely adjusted. This is in contrast to the case of the online counter, where a wrong input phase could suppress the signal without the possibility of recovering it in post-processing. The enhancement in fluorescence of the excited sodium atoms when modulating in resonance with the Larmor precession (referred to as contrast) was measured as 18% above the photon flux out of resonance as shown in Fig. 6.6b. In addition, the lock-in amplifier demodulated the incoming signal into phase and quadrature components, calculating in real time the time-evolution of the resonance, useful for tracking slowly varying magnetic signals. A time constant of 300 ms was used for all measurements with lock-in amplifier.
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Figure 6.6: Magneto-optical resonances. The resonances were obtained by sweeping the frequency of the intensity-modulated laser beam with three concurrent data acquisition methods. 

a Online differential counter for a modulation duty cycle of 20% and $I_{\text{meso}}^{\text{avg}} = 13$ W m$^{-2}$. The Larmor frequency lies in the center between the peaks, which are separated by twice the dither excursion $\delta f = 20.2$ kHz. 

b Ratio of the photon counts per dither period averaged over 2 s. The modulation duty cycle was 30%, excursion $\delta f = 30.8$ kHz and calculated mesospheric irradiance $I_{\text{meso}}^{\text{avg}} = 33$ W m$^{-2}$. 

c Lock-in amplifier with time constant of 300 ms, modulation duty cycle 20%, excursion $\delta f = 30.8$ kHz, and calculated mesospheric irradiance $I_{\text{meso}}^{\text{avg}} = 17$ W m$^{-2}$. For all resonances, a double Lorentzian fit shows a broad and a narrow width of $\approx 30$ and 2 kHz, respectively, consistent with two relaxation mechanisms due to velocity-changing collisions (fast) and spin-exchange collisions (slow) of sodium with N$_2$ and O$_2$ molecules. The residuals of the fits are shown below each resonance and obey a normal distribution according to the Gaussian fit of the residuals histograms.
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The demodulated signals, consisting of a positive and a negative peak, were fit with superimposed Lorentzians (Fig. 6.6), following the outcome of a numerical model which is discussed below. The Larmor frequency was estimated as the mid-point between the two peaks. The residuals from the lock-in amplifier signal display small deviations from the fit that may be attributed to slow altitude displacements of the sodium layer centroid during the sweep. Upward displacement of the sodium centroid toward a weaker magnetic field region produces a shift of the magnetic resonance toward lower frequencies, resulting in asymmetries of the observed resonance.

The measured Larmor frequencies from 51 runs are plotted in Fig 6.7. The average Larmor frequency was found to be 260.4(1) kHz, representing a geomagnetic field of 0.3720(1) G according to Eq. 6.1. The WMM2015 prediction for the magnetic field at 92 km altitude is 0.3735(15) G, giving a difference of $<0.5\%$ between the model and our observations. Since the magneto-optical signal comprises the contribution from all sodium atoms weighted by their density distribution along the laser interrogated column in the mesosphere, the measured Larmor frequency is most strongly representative of the geomagnetic field at the sodium centroid position. Indeed, due to magnetic field gradients in the vertical direction $H$ in the mesosphere of $dB/dH = -1.85 \cdot 10^{-4}$ G km$^{-1}$ (Chulliat et al. 2015), equivalent to a Larmor frequency gradient of $df_L/dH = -0.129$ kHz km$^{-1}$, the position of the Larmor frequency in the magneto-optical resonance could lie at any point within the light-red band shown in Fig. 6.7 depending on the position of the sodium centroid at the time of the observation.
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Figure 6.7: Measured Larmor frequency from 51 runs. The red dashed line is the median of all observations. The horizontal light-red band represents the predicted magnetic field between 85 and 100 km altitude according to the WMM2015 magnetic model (Chulliat et al. 2015). Error bars are the standard error of the estimate of $f_L$.

In addition, spatially separated sodium density peaks (sporadic sodium layers) (Clemesha 1995) broaden the magneto-optical resonance as a result of atomic spins precessing at different Larmor frequencies due to magnetic field gradients within the sodium layer. Sporadic sodium layers in the mesosphere at La Palma have been detected on average once per night with lifetime from 30s to several hours (Michaille et al. 2001), which makes our technique susceptible to this effect. The spatial accuracy of the magnetic-field measurements could be improved if the vertical sodium profile were independently known, for example, from simultaneous lidar (light detection and ranging) measurements. Because of the absence of such profiles during the present experiment, there is an intrinsic uncertainty in the altitude of the magnetic-field measurements.

Magnetometry. To measure the absolute magnetic field in the mesosphere, a full scan of the magneto-optical resonance was performed so that the Larmor frequency could be determined. If it is desired to measure fluctuations in the magnetic field, the magnetometer can operate with an intensity-modulation frequency fixed at the maximum-sensitivity point along the resonance curve. In this case, magnetic-field variations are reflected in changes of the amplitude
of the demodulated signal or in changes of the frequency feedback signal needed to keep the magnetometer locked at a certain point of the resonance curve.

Figure 6.8: Estimate of magnetometry accuracy. **a** A resonance acquired with the lock-in amplifier in good atmospheric conditions (seeing 0.7 arcsec) with $\delta f = 8 \text{ kHz}$. **b** Magnetometry accuracy level from the derivative of the resonance fit function. The maximum sensitivity of $0.28 \text{ mG Hz}^{-1/2}$ is achieved at the steepest points of the resonance.

In order to estimate the accuracy of the Larmor-frequency measurements and magnetic-field fluctuations, we use data from a single run with $\delta f = 8 \text{ kHz}$ and $f_m = 150 \text{ Hz}$, as shown in
6.2. Remote sensing of geomagnetic fields and atomic collisions in the mesosphere

Fig. 6.8a. The Larmor frequency for this run is 260.12 kHz, corresponding to 0.37170 G, with a standard error for $f_L$ of 0.04 kHz (or 0.05 mG). The existence of the narrow peaks in the magneto-optical resonances found in this experiment strongly reduce the uncertainty in the estimate of the Larmor frequency. The highest magnetic-field sensitivity can be found at the minimum of the differentiated fit function of the resonance in Fig. 6.8b. At the middle point between the two peaks of the reference magneto-optical resonance shown in Fig. 6.8a, the calculated accuracy is 1.24 mG Hz$^{-1/2}$, similar to that reported in Kane et al. (2018). The highest sensitivity is provided by the slope of the narrower of the two superimposed Lorentzians, where an accuracy of 0.28 mG Hz$^{-1/2}$ can be reached.

In this experiment, a median value of about $12 \cdot 10^3$ counts s$^{-1}$ was measured during frequency scans, which corresponds to shot noise near 100 counts s$^{-1}$ or $\approx 1\%$. The estimate of the noise contributions from the noise analysis shows a noise floor near $10^{-2}$ Hz$^{-1/2}$, indicating a shot-noise-limited measurement. Random fluctuations of the centroid and the sodium layer profile are strong contributors to the uncertainty in the estimation of the geomagnetic field at a given point in the sodium layer.

6.2.2 Discussion

The fundamental sensitivity of an optical magnetometer is determined by the total number of atoms, the spin-relaxation rate in the atomic medium, and the measurement duration (Kimball et al., 2013). At ORM, an average column density of $C_n = 3.6 \cdot 10^{13}$ atoms m$^{-2}$ was measured with lidar observations (Michaille et al., 2001). From long-term observations of the sodium layer at low geographic latitude, the average sodium centroid height was determined to be 92 km above sea level with a thickness of 11.3 km (Moussaoui et al., 2010). The spin relaxation in the mesosphere is dominated by collisions and the finite transit time of the polarized atoms across the laser beam. For a sodium atom, most collisions occur with N$_2$ and O$_2$ molecules, whereas Na-Na collisions are less frequent due to the low sodium density. While collisions of sodium with any molecule change the velocity of the atoms, Na-O$_2$ collisions are primarily responsible for spin relaxation due to the large exchange interaction between unpaired electrons of O$_2$ and sodium (Morgan & Happer, 2010). The Na-O$_2$ collisions determine the highest spin-relaxation rate in the atomic system [on the order of $1/(250\mu s)$] and limit the sensitivity to magnetic-field measurements by broadening the magneto-optical resonance. In the mesosphere, the diffusive transit of sodium atoms across the laser beam is expected to be one order of magnitude longer.
than the relaxation time given by Na-O_2 collisions. Considering the aforementioned values of sodium density and spin-relaxation rate, the fundamental spin-projection-noise-limited sensitivity (quantum limit) is on the order of 10^{-11} G Hz^{-1/2}. However, primarily due to the small solid angle for the fluorescence collection (\approx 10^{-11} \text{ sr} for a 0.4 m diameter receiver telescope), a shot-noise-limited sensitivity on the order of 10^{-4} G Hz^{-1/2} can be achieved.

The sensitivity can be affected by instabilities of the sodium layer. The sodium atomic density in the mesosphere is highly variable on all relevant time scales. Continuous monitoring of the sodium-layer density profiles with lidar techniques shows structural and density changes with time scales of minutes (Pfrommer & Hickson 2010). Sporadic events caused by the advection of meteor ablation from the ionosphere into the mesosphere produce sodium density changes over time scales of seconds (Clemesha et al. 2004). In addition, atmospheric scintillation imposes another strong source of noise for an optical magnetometer. The power spectrum of scintillation was characterized at La Palma and shows a steep decrease for frequencies above 10 Hz for telescope apertures similar to those used in our experiment (Dravins et al. 1998). We have reached a sensitivity near the shot-noise limit, meaning that the approach of dithering the intensity modulation of the laser at a frequency of 150 Hz effectively removed most of the intensity noise due to scintillation.

Numerical modeling of the time evolution of the sodium atomic polarization under resonant pulsed excitation using the density-matrix model described in Rochester et al. (2012) shows a magnetic resonance that can be fitted with two superimposed Lorentzians of different widths. The superimposed Lorentzians (see also Fan et al. (2016)) are analogous to the nested dispersive Lorentzians observed in nonlinear magneto-optical rotation (NMOR) with antirelaxation-coated vapor cells (Budker et al. 2002). In such NMOR experiments, a transit effect is observed with a resonance width corresponding to the rate at which atoms traverse the light beam. Moreover, a wall effect due to atoms leaving and then reentering the light beam after bouncing off of the cell wall, shows a narrower width corresponding to the relaxation rate of atomic ground-state polarization. In the present case, rather than considering the atomic positions relative to the light beam, we must consider atoms leaving and reentering the resonant velocity group of the Doppler distribution. Then, the broad resonance arises from precessing atoms leaving the resonant velocity class due to velocity-changing collisions (a type of transit effect within the Doppler distribution). On the other hand, the narrower resonance is determined by the polarization relaxation rate due to spin-exchange collisions in all velocity groups. The width of
each feature equals $1/(\pi \tau)$, where $\tau$ is the corresponding relaxation time. The effect of varying the rate of velocity-changing ($\gamma_{vcc}$) and spin-exchange ($\gamma_s$) collisions is shown in simulated resonance curves obtained from our model (Fig. 6.9).

Figure 6.9: Numerical modelling of the magneto-optical resonance. We assume a laser irradiance of $I_{\text{meso}} = 15 \text{ W m}^{-2}$ in the mesosphere, and excursion of $\delta f = 30 \text{ kHz}$. The central dashed line indicates the Larmor frequency, $\gamma_{vcc}$ denotes velocity-changing collision rates, and $\gamma_s$ spin-exchange collision rates.
Fitting experimental data with a double Lorentzian function and estimating the widths yields FWHM median values of $\delta f_{\text{broad}} = 32$ kHz for the broad resonance component, and $\delta f_{\text{narrow}} = 2.4$ kHz for the narrow resonance component. According to our numerical simulations the observed widths are obtained with a velocity-changing collision rate on the order of $\gamma_{\text{vcc}} \approx 1/(10 \mu s)$ and a spin-exchange rate on the order of $\gamma_s \approx 1/(100 \mu s)$. These results suggest that collision rates in the mesosphere are higher than previous estimates by a factor of 2-6. For instance, a mean spin-exchange collision rate of $\gamma_s = 1/(490 \mu s)$ was estimated in Holzlöhner et al. (2010). Other estimates suggest values of $\gamma_s 1/(200 \mu s)$ (Li et al. 2016), and $\gamma_s = 1/(640 \mu s)$ (Milonni et al. 1999). While other methods to evaluate the sodium spin-exchange collision rate depend on estimates of the atomic collisional cross-section between Na and other species, we provide a relatively direct measurement of $\gamma_s$. This value could be used, based on first principles, to calculate the actual Na-O$_2$ cross-section in the mesosphere (to the best of our knowledge no experimental measurement of the Na-O$_2$ spin-exchange cross-section at mesospheric conditions has been reported).

The discrepancy between collision rates estimates may be due to bias in the assumed cross-sections, large magnetic field gradients, and/or uncertainty in the sodium profile. In order to identify the reason for this discrepancy, quantitative measurements, development of an improved collision model, and parallel sodium profile measurements with lidar could be used.

We have demonstrated a method of remote magnetic field measurements in the mesosphere using a laser beam with intensity modulation at the Larmor frequency of sodium, achieving an accuracy of 0.28 mG Hz$^{-1/2}$. This work contributes to several efforts in the scientific community to develop techniques for remote sensing of magnetic fields in the atmosphere (Kane et al. 2018; Johnson et al. 2014; Davis et al. 1989). We note that the setup used in this experiment can, in principle, be realized with components such as laser sources, modulators, and telescopes currently available commercially. Our observations show good agreement with the predictions of the geomagnetic field from the World Magnetic Model for altitudes between 85 and 100 km, and could provide input data for future assessments of this model. Further improvement of the method is possible. For instance, with laser power high enough to saturate the resonant velocity class, one can expand the beam to increase the total number of interrogated atoms. Furthermore, observing the magneto-optical resonance at short vertical sections of the elongated fluorescent column in the mesosphere can reduce the effect of broadening due to magnetic-field gradients. We found that the magneto-optical resonant signal contains broad and narrow
features that depend on specific kinds of atomic collisions. The method presented in this work shows that atomic collision rates can be inferred from the observed resonances, suggesting another important application of this approach: remote sensing of collisional processes in the mesosphere.
Chapter 7

Polarization-driven spin precession of mesospheric sodium atoms

A version of this chapter has been published by F. Pedreros Bustos, D. Bonaccini Calia, D. Budker, M. Centrone, J. Hellemeier, P. Hickson, R. Holzlöhner and S. Rochester, “Polarization-driven spin precession of mesospheric sodium atoms” in Optics Letters.

The development of techniques for controlling atomic spins has resulted in stable atomic frequency standards (Vanier & Tomescu 2015), high resolution spectroscopy (Suefke et al. 2017), and precise and accurate optical magnetometers (Sheng et al. 2013). Particularly, the measurement of magnetic fields with high sensitivity using optical magnetometers has had a broad impact, from tests of fundamental physics to biomedical and geophysical applications (Budker & Romalis 2007). Recently, the demonstration of optical magnetometry using naturally occurring sodium atoms in the upper mesosphere (between 85 and 100 km altitude) opened the way for new scenarios for research in this complex and uncontrolled environment (Kane et al. 2018; Bustos et al. 2018). The remote detection of magnetic fields in the mesosphere brings opportunities for the study of scientific phenomena, including ionic currents from oceanic tides (Tyler et al. 2003), dynamics in the upper mantle subduction zones (Blakely et al. 2005), and electric current fluctuations in the ionosphere (Yamazaki & Maute 2017).

The principle of an optical magnetometer is to measure the response of an atomic medium to magnetic fields using light. In particular, resonant polarized light can be employed to selectively populate energy levels in an atomic ensemble. This mechanism, called optical pumping (Happer 1972), creates spin polarization in both the ground and excited states of the medium. The action of an external magnetic field B produces precession of the atomic magnetic moments around the magnetic field at a rate given by
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\[ f_L = \gamma/(2\pi)|B|, \]  

(7.1)

where \( f_L \) is the Larmor frequency, \( \gamma \) is the gyromagnetic ratio of the atomic species, and \( B \) is the magnetic field. For sodium, the ground-state gyromagnetic ratio is \( \gamma = 699.812 \) kHz/G. When the medium is pumped with light modulated at \( f_L \), a high degree of atomic polarization can be obtained, as the atomic spins are driven synchronously with the precession during optical pumping (Bell & Bloom 1961; Alexandrov et al. 2005). This results in a resonance in the response of the medium whose frequency is proportional to the strength of the external magnetic field, and gives the basis for absolute and precise magnetic field measurements.

Traditional synchronous optical pumping schemes in optical magnetometers are based on intensity- or frequency-modulated light. In contrast, we pump with polarization-modulated light. This idea was first explored for studying quantum interference in atomic systems (Aleksandrov 1973) and later extended as an alternative mechanism to induce magnetic resonances in atomic magnetometers (Fescenko et al. 2013; Grujić & Weis 2013). Recently, using a polarization-modulated continuous-wave (CW) laser beam was proposed for increasing the fluorescence of mesospheric sodium and for remote measurement of magnetic fields (Fan et al. 2016). In this Letter, we realize this approach in an on-sky experiment and report the observation of a magnetic resonance when modulating the laser polarization at the Larmor frequency.

The pumping process is schematically depicted in Fig. 7.1. Photons with left-handed circular polarization (\( \sigma^- \)) are absorbed and drive transitions from ground to an excited state with \( \Delta m = +1 \), where \( m \) is the magnetic quantum number. The atoms then spontaneously decay. This increases the atomic spin polarization along the light propagation direction. However, if a magnetic field is applied perpendicular to the light propagation direction, atomic spins Larmor-precess around this field. Half of the Larmor period \( 1/2f_L \) after pumping, the ground-state spin polarization points counter to the light propagation direction, and further pumping with left-handed circular polarization only depolarizes the medium. However, with the atomic polarization pointing in this direction, right-handed circular polarization (\( \sigma^+ \)) can be used to increase the spin polarization; by continued polarization switching every half-Larmor cycle, atoms can be pumped to the \( |m| = F \) end states. This increases the return flux by confining atoms to strong cycling transitions with fluorescence preferentially along the laser propagation.
axis.

Figure 7.1: Simplified diagram of the hyperfine structure of sodium, including magnetic sublevels. The quantization axis is chosen along the direction of the light propagation. Alternating circularly polarized light (thick orange arrows) at the Larmor frequency increases spin polarization in the $|F = 2, m = \pm 2\rangle$ states. $\sigma^+$ denotes left-handed circular polarization, and $\sigma^-$ denotes right-handed circular polarization. The thin orange arrows indicate repumping used to recover lost in the $|F = 1\rangle$ ground state.

The experiment was carried out at the Observatorio del Roque de los Muchachos, La Palma, during April 18-19, 2018. The experiment is schematically presented in Figure 7.2. The laser system was built by the European Southern Observatory (ESO) as a prototype for the new generation of laser guide star devices (Calia et al., 2012). A master oscillator power amplifier (MOPA) laser produces a 40 W CW beam at 1178 nm. The second-harmonic generation (SHG) crystal doubles the frequency of the infrared beam, producing up to 20 W CW with a vacuum wavelength of 589.158 nm and a linewidth of $\approx 2$ MHz (respectively, measured with a wavemeter and a Fabry-Perot spectrum analyzer). A function generator (Rigol 1062Z) followed by a power amplifier supplies a high-voltage signal to a custom-made broadband electro-optic modulator (EOM, Qubig D7v-R3-589). The electric field applied to the EOM crystal introduces the modulation of polarization of the laser beam. The beam is expanded through a Galilean telescope to a diameter of 30 cm. Photons emitted from the sodium layer are collected on the ground with
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a commercial telescope of 35 cm diameter (Celestron EdgeHD 14) placed eight meters from the laser-launch telescope. A custom-made photometer consists of a pinhole placed at the focal plane of the telescope to isolate the sodium fluorescent spot, a narrow-band filter of 0.30(5) nm bandwidth centered at the resonant wavelength of sodium, and a photomultiplier tube (PMT, Hamamatsu H7422). The analog photon-detection pulses from the PMT are filtered and amplified with a discriminator (Ortec 9327, not shown) producing clean transistor-transistor logic (TTL) pulses of 100 ns width. Individual pulses are time-tagged, recorded, and transferred to a computer with a fast time-to-digital converter (TDC, Roithner LaserTechnik TTM8000). A custom-made integrator amplifier (not shown) with a -1 dB bandwidth of 900 Hz converts the sequence of TTL pulses into a slowly varying signal whose amplitude is proportional to the photon flux in the magnetic resonance region. This signal is fed into the lock-in amplifier (LIA, Stanford Research SR865) that demodulates and extracts in real time the root-mean-square amplitude of the alternating component. With this approach, two parallel acquisition systems (TDC and LIA) provide redundancy and independent outputs for cross-checking.

The polarization of the laser beam was calibrated with a polarimeter (Thorlabs PAX5710VIS-T) placed at the output of the laser projector. A high-voltage signal of approximately ±350 V was used to drive the EOM at low frequency (Figure 7.3). A maximum ellipticity excursion of ±30° was achieved (the full σ+ to σ− range is ±45°). We suspect that thermal birefringence due to heat transfer to the crystal when operating at high optical power, combined with a limited maximum voltage that can be supplied to the EOM, prevented us from reaching 45°-ellipticity in the current setup. Proper crystal thermal management, as well as improvements in light polarization purity through the optical elements of the laser head, will be established for future experiments. The use of polarization-modulated light in this approach has several advantages with respect to the intensity modulation used previously, for instance, the increase of the average photon return flux at fixed laser power, increasing the signal-to-noise ratio (SNR) for detection on the ground. The atmosphere does not impose a serious limitation regarding depolarization of the pump laser beam due to propagation through the turbulent layers, as shown by theoretical models and experiments on optical communications, where the depolarization due to the atmosphere was found to be less than 1% (Collett & Alferness 1972; Toyoshima et al. 2009).

Scintillation due to atmospheric turbulence produces brightness fluctuations of the fluorescent sodium when seen from the surface of the Earth (a phenomenon commonly known as “star twinkling”) that manifests in this experiment as detrimental intensity noise. To address the
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Figure 7.2: Schematic of the experimental arrangement. MOPA, master oscillator power amplifier laser; SHG, second-harmonic generation; EOM, electro-optic modulator; PMT, photomultiplier tube; TDC, time-to-digital converter; LIA, lock-in amplifier; FG, function generator. The diagram in the upper-left corner indicates the orientation of the atomic spins with the time varying polarization of the laser beam.

effects of scintillation, we dither the modulation frequency at a higher rate than the scintillation variations during the scan. Dithering the modulation frequency during the scan can also be beneficial in suppressing intensity fluctuations derived from thin cirrus clouds and density fluctuations in the sodium layer. The power spectrum of scintillation from stars measured at La Palma falls above 100 Hz \cite{Dravins1998}; thus, we choose a dither frequency of $f_m = 300$ Hz. The frequency of the polarization modulation is given by Equation 6.2. For this experiment, the excursion was chosen as $\delta f = 15$ kHz in order to resolve narrower magnetic resonance features predicted by numerical simulations.
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Figure 7.3: Ellipticity of the laser beam measured at the output of the launch telescope. Here the modulation frequency is much lower than the Larmor frequency due to limitations of the polarimeter response. The polarization ellipses at the maximum and minimum ellipticity are also shown.

The received signal must be demodulated to extract the magnetic resonance. The demodulation was carried out with a LIA to detect the amplitude and phase of the signal component oscillating at $f_m$ and, independently and in parallel, by calculating the ratio of photon counts within consecutive semi-cycles of the dither period. The demodulated signal shows a point symmetric dip and peak, separated by $2\delta f$, corresponding to the rising and falling slopes of the magnetic resonance probed during the frequency scan. The demodulation process produces the output $S(f_{step} + \delta f) - S(f_{step} - \delta f)$, where $S(f_{step})$ is the flux at $f_{step}$, resulting in two opposite sign copies of the original magnetic resonance $S(f)$ separated by $2\delta f$.

The results of two scans performed at an elevation of 64° and azimuth of 3° on April 18, 2018, are shown in Fig. 7.4. The total laser power output was 12.5 W of which 10% was used for D2b repumping (sideband at 1713 MHz from resonance). The angle between the geomagnetic field and the laser beam was $\theta_B = 80^\circ$. The frequency axis shows the value of $f_{step}$ during the scan. Each peak is fitted with a double Lorentzian, representing broad and narrow components of the resonance. The Larmor frequency is found at the midpoint between peaks and is a free parameter of the model, in addition to the amplitude and width of the peaks. The separation of the peaks is fixed at $2\delta f$. The geomagnetic field predicted by the World Magnetic Model
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2015 (WMM2015) (Chulliat et al. 2015) at 85 and 100 km altitudes in the direction of pointing is 0.3731(15) G and 0.3703(15) G, respectively, which, from Equation 7.1, corresponds to a Larmor frequency of 261.1(1.0) and 259.2(1.0) kHz. The estimates of the Larmor frequency obtained from the fitting of the resonances shown in Figure 7.4 are 259.7(3) and 260.3(4) kHz, close to the prediction of the WMM2015 at altitudes within the boundaries of the sodium layer (as also shown in Figure 7.4). The combined error of the estimated Larmor frequencies in Figure 7.4 is 0.2 kHz, corresponding to 0.3 mG, according to Equation eq: Larmor-paperII.

The reading of our sky magnetometer, in principle, can be affected by vertical winds in the mesosphere and fast transient spikes in the sodium density within the sodium layer (Pfrommer & Hickson 2014), leading to atoms precessing at different Larmor frequencies due to vertical magnetic field gradients \( \frac{d\beta}{dH} = -1.83 \times 10^{-4} \) G/km at La Palma, according to the WMM2015. For these reasons, parallel measurements of the vertical sodium density profile, for example, using a light detection and ranging system, as well as observing the fluorescence from small vertical layers of the sodium profile, could help to increase the accuracy of the Larmor frequency measurement in the vertical direction.

The resonance of Figure 7.4 shows a flux enhancement of 4% at the Larmor frequency with respect to the flux at a modulation frequency of 230 kHz. The total photon-count rate during the scan is shown in the inset figure for each magnetic resonance in Figure 7.4. The strong fluctuations in the photon flux during the scan are a result of atmospheric turbulence and the sporadic presence of variable thin layers of dust in the troposphere due to the Saharan Air Layer over the Canary Islands. The reduction of the photon flux towards the end of the scan [inset Figure 7.4(a)] and the oscillating flux during the scan [inset Figure 7.4(b)] are consequences of the tracking errors in the receiver telescope which resulted in the fluorescent spot not being perfectly centred in the pinhole prior to the photomultiplier. The noise seen in the magnetic resonance is primarily due to shot noise and the residual effect of high-frequency scintillation.

Numerical simulations of the time evolution of the sodium atomic polarization using a density-matrix model (Holzlöhner et al. 2010) show that the measured signal in our setup can be well described by two superposed Lorentzians (Figure 7.5). This observation supports our choice of fit functions of the magnetic resonances shown in Figure 7.4. In addition, the return-flux enhancement found from modeling shows good agreement with the data using the estimated experimental conditions for the measurements. The parameters used to simulate the magnetic
Table 7.1: Simulated parameters with the corresponding symbols and values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam transit rate</td>
<td>$\gamma_{beam}$</td>
<td>$1/(5 \text{ ms})$</td>
</tr>
<tr>
<td>Velocity-changing collisions rate</td>
<td>$\gamma_{vcc}$</td>
<td>$1/(15 \mu\text{s})$</td>
</tr>
<tr>
<td>Spin-damping collisions rate</td>
<td>$\gamma_s$</td>
<td>$1/(150 \mu\text{s})$</td>
</tr>
<tr>
<td>Mesospheric temperature</td>
<td>$T_{meso}$</td>
<td>200 K</td>
</tr>
<tr>
<td>Laser irradiance in the mesosphere</td>
<td>$I_{meso}$</td>
<td>36 W/m$^2$</td>
</tr>
<tr>
<td>Laser linewidth</td>
<td>$\Delta f$</td>
<td>2 MHz</td>
</tr>
<tr>
<td>D$_{2b}$ repumping frequency offset</td>
<td>$f_{D_{2b}}$</td>
<td>1713 MHz</td>
</tr>
<tr>
<td>Repumping fraction</td>
<td>$q$</td>
<td>10 %</td>
</tr>
<tr>
<td>Gyromagnetic ratio of sodium</td>
<td>$\gamma/(2\pi)$</td>
<td>699.812 kHz/G</td>
</tr>
<tr>
<td>Magnetic field strength</td>
<td>$B$</td>
<td>0.371 G</td>
</tr>
<tr>
<td>Magnetic polar angle</td>
<td>$\theta_B$</td>
<td>80°</td>
</tr>
</tbody>
</table>

Resonance shown in Figure 7.5 are given in Table 7.1. Simulations also show that the broad Lorentzian resonance is centered at a slightly different frequency off the narrow resonance at high irradiance. This effect is due to the light shift due to real transitions (Bulos et al. 1971) in which atoms precess in the excited state at a different frequency compared to that of the ground state; however, we expect to observe the shift in future measurements with a better SNR.

In conclusion, we have observed for the first time, to the best of our knowledge, the atomic spin precession of mesospheric sodium induced by modulating the polarization of a resonant CW laser beam at 589.158 nm. Severe weather conditions at La Palma allowed only two nights of observations. Therefore, additional measurement campaigns are foreseen to carry out a more complete study of the parameter space in order to understand the merits and shortcomings of this approach, and to compare the magnetometry performance of polarization modulation with respect to the intensity modulation scheme. Immediate possible applications include the mapping of geomagnetic fields at mesospheric scales and boosting the brightness of sodium laser guide stars when pointing in directions with large angles between the laser beam and the geomagnetic field lines.
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Figure 7.4: Demodulated magnetic resonances obtained from (a) the ratio of photon counts and (b) with a LIA. Each resonance consists of one peak and one dip representing two copies of the original resonance. The Larmor frequency is found in the midpoint between peaks (dashed lines). The thick line is a fit of two superimposed Lorentzians separated by $2\delta f$. The vertical red band represents the Larmor frequency corresponding to the geomagnetic field between an 85 and 100 km altitude, according to the WMM2015. The gray vertical band indicates the uncertainty of the prediction from the WMM2015. The inset figures show the photon-count rate during the frequency scan.
Figure 7.5: Numerical simulations of the magnetic resonance (dots) and a double Lorentzian model (line), where $a_{1,2}$ are the amplitudes, $f_{1,2}$ are the central frequencies, $\sigma_{1,2}$ are the full-width at half-maximum of each Lorentzian, and $b$ is an offset.
Chapter 8

Continuous-wave lidar

In this chapter a technique for obtaining sodium density profiles from CW laser induced LGS will be presented. The technique is based on amplitude modulation of CW lasers by pseudo-random binary sequences (PRBS). The technique has been tested at the LZT, Maple Ridge, Canada in July 2014. Results from this experiment and a performance analysis for an ELT setting based on numerical simulations are presented. The experiment was carried out by D. Bonaccini Calia, P. Hickson, A. Otarola and T. Pfommer. I was responsible for the data analysis, numerical simulations and the preparation of a paper. The paper includes a section on an analytical performance estimate which has been mainly contributed by P. Hickson.

8.1 Sodium density profile variations

Atomic sodium only exists in the atmosphere in a layer spanning from 80 km to 120 km altitude in the mesosphere. The mesosphere is the coldest region in the atmosphere. The regions adjacent to the mesosphere are heated by ultraviolet (UV) and infrared radiation. The higher thermosphere is heated by UV-radiation and the lower stratosphere is mainly heated by absorption of infrared radiation by (water) molecules. The mesosphere contains Na, K, Fe, Mg, Ca, Si, six atomic species which in principle could be used for LGS (Plane et al. 2015). Transition lines of these elements can be found in terrestrial nightglow. The sodium D$_2$-line is used for LGS systems since it has the highest product of cross-section and element abundance, which yields the highest LGS return flux. Initially, high-powered lasers at 589 nm were not commercially available, but were developed over time as laser technology evolved. The development of frequency-doubled, narrow-band Raman-fibre lasers facilitated output powers of 20 W. However, transition lines of different elements for LGS are being studied, especially since sodium might not be abundant enough to allow backward-directed modeless lasing. For studies of atmospheric dynamics, lidar systems using sodium, potassium and iron transitions have been used (Gardner 1989; Schäfer et al. 1994). The origin of the atomic sodium, like the origin of the other elements, in the mesosphere is not completely known. Deposition by ablation of meteors
8.1. Sodium density profile variations

Figure 8.1: Sodium layer evolution at the LZT, from Pfommer et al. (2009)

The sodium density profile variations are best-explained (Clemesha et al. 1978). The atomic sodium is infused into the layer by ablation and then slowly sinks until it reaches the lower boundary of the layer, at which point the atmospheric density is high enough to permit sodium to react with other atoms or molecules. Most reactions binding the atomic sodium are between oxygen and sodium. This results in a lower edge of the layer being well-defined. The centroid is typically situated at an altitude of about 90 km and the FWHM of the layer is around 10 km. The sodium column density is on the order of magnitude $10^{13} \text{m}^{-2}$ (Von Zahn et al. 1988). The sodium abundance shows seasonal trends in which the lowest column densities occur during summer and the highest in winter (Gardner et al. 1988; Hedin & Gumbel 2011). These trends are more pronounced at higher latitudes. Despite the seasonal trends, the global sodium abundance in the Earth’s atmosphere is roughly constant, with alternating column densities by seasons (Clemesha et al. 1992). The sodium column density not only shows seasonal variations but also fluctuates by factors of 2-4 during single nights (Fan et al. 2007). Typically, the column density is lowest around midnight, and highest around dusk and dawn.

The sodium layer in the mesosphere has been intensively studied by geophysicists, since the 1980’s. Sodium density structure is subject to strong atmospheric forcing and shows a dynamic evolution. Sometimes the rapid formation of high-density layers, so-called sporadic sodium layers, can be observed (Batista et al. 1989). Lidar systems employed in these studies, generally having small aperture sizes, were able to map the sodium density structure on timescales of a few minutes. However, for AO systems, being updated on the order of 1 kHz, studies with higher temporal resolution were needed. Particularly, the temporal power-spectrum of the
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Figure 8.2: A meteor trail crossing the field of view of the LZT lidar. The data were taken on 2010-07-25 by T. Pfrommer.

sodium-layer centroid is of importance, which will be explained later. The need for sodium lidar systems with high-temporal resolution led to equipping the LZT with a high-resolution lidar system (Hickson et al. 2007; Pfrommer et al. 2009). The LZT with its 6-m diameter mirror was able to provide sub-second temporal resolution for studies of the sodium density structure. The studies conducted at the LZT revealed gravity waves, Kelvin-Helmholtz instabilities and turbulent structures in the sodium layer (Pfrommer & Hickson 2010, 2014). A power law index of about $-2$ was found for sodium profile centroid fluctuations. The temporal evolution of the sodium layer and a meteor trail crossing the aperture can be seen in Figure 8.1 and Figure 8.2.

AO system performance is reduced by centroid variations, with a greater effect occurring for larger telescope apertures. The LGS appears spot-like when viewed from directly below, but is actually a column of fluorescent sodium in the mesosphere. When viewed with a small
8.1. Sodium density profile variations

horizontal offset, the LGS becomes extended. Increasing the offset enlarges the size of the LGS image. Variations in the sodium density structure cause intensity variations of the LGS image. These intensity variations decrease the AO system performance. The main decrease in system performance is caused by focus errors. Focus is corrected by sensing of NGS. For an increased sky coverage NGS are sensed at lower frequencies than LGS to allow for sufficient integration time in the case of dimmer stars. If the sodium density structure changes in between NGS update cycles, the wavefront sensing error increases. The fast-sampling LGS control loop will adjust the Zernike focus term due to two reasons. The focus term is changed when the atmospheric turbulence above the telescope changes. This is a wanted effect, since it is the task the AO system is designed for. But, the focus term will also change when the sodium centroid changes, since the LGS control loop can not distinguish these changes from changes in atmospheric focus. In addition higher order wavefront errors are induced by LGS intensity variations. Since the offset increases with increasing aperture size, the wavefront sensing degradation increases for larger telescopes (Thomas et al. 2011). The RMS wavefront error from defocus, averaged over the telescope pupil, can be derived from the geometry of the LGS imaging (Davis et al. 2006; Herriot et al. 2006). For observations at the zenith

$$\sigma_{wf} = \frac{1}{16\sqrt{3}} \frac{D^2}{\bar{z}^2} \sigma_{\bar{z}},$$

(8.1)

where $D$ is the telescope diameter, $\bar{z}$ the sodium centroid altitude above the telescope and $\sigma_{\bar{z}}$ the change in sodium centroid altitude. The RMS wavefront error increases with increasing telescope diameter. An illustration of the focus error arising from centroid variations is shown in Figure 8.3 The TMT error budget foresees 12 nm for wavefront error from sodium centroid fluctuations Gilles et al. (2008), the ELT allocates 60 nm\footnote{internal communications with D. Bonaccini Calia and T. Morris}.

Continuously monitoring the line-of-sight sodium density profile could overcome the problem of centroid variation. Sodium profiles could be retrieved by the time-of-flight measurement of short-pulsed lasers, but short-pulsed lasers produce a lower average LGS return flux than CW lasers. For CW lasers it is possible to retrieve sodium density profiles, by amplitude modulation of the laser power with PRBS. This method will now be presented.
8.2 CW lidar method

Butler et al. (2003) were the first to obtain sodium density profiles by the CW lidar method. The method uses partial or entire amplitude modulation of a CW laser signal. For a modulated laser beam, exciting a single layer of sodium at distance \( d \) with infinitesimal thickness \( dz \), the return flux of the LGS will show the same modulation pattern at a delay of \( 2z/c \). The return flux \( s(t) \) from an extended sodium layer can be calculated by the integral over the modulation function \( g(t) \in [0,1] \), weighted by the sodium density profile,

\[
s(t) = s_0 \int_0^\infty g(t - 2z/c)f(z)dz. \tag{8.2}
\]

\( s(t) \) is the number of photons arriving per second, \( s_0 \) is the return flux when there is no modulation and \( f(z) \) is the flux weighted sodium profile\(^8\)

\[
f(z) \propto \rho(z)z^{-2}, \tag{8.3}
\]

\(^8\)Since AO system algorithms use flux weighted density profiles for wavefront reconstruction, our goal is to obtain the flux weighted density profile.
8.2. CW lidar method

where $\rho(z)$ is the sodium density profile. By defining $f(z)$ to be zero for negative $z$ the lower limit of the integration in Equation 8.2 can be set to $-\infty$. With the substitution $\tau = 2z/c$ the equation can be rewritten as

$$s(t) = \frac{cs_0}{2} \int_{-\infty}^{\infty} g(t - \tau)f(\tau)d\tau,$$

$$= \frac{cs_0}{2} g(t) * f(t), \quad (8.4)$$

where $*$ is the symbol for convolution. $*$ will be used in the following for cross-correlations. The return flux is proportional to the convolution of the modulating sequence and the flux-weighted sodium density profile. If a modulation sequence with a delta-like autocorrelation function was used, then an estimate of the sodium density profile can be obtained by the cross-correlation of the modulation sequence and the LGS return flux signal

$$g(t) * s(t) = \frac{cs_0}{2} g(t) * (g(t) * f(t)),$$

$$= \frac{cs_0}{2} g(t) * (g(t) * f(-t)),$$

$$= \frac{cs_0}{2} (g(t) * g(t)) * f(-t),$$

$$= \frac{cs_0}{2} (g(t) * g(t)) * f(t),$$

$$\approx \frac{cs_0}{2} \delta(t) * f(t) = \frac{cs_0}{2} f(t), \quad (8.5)$$

For the method it is mandatory to use a modulation sequence which has a delta-like autocorrelation

$$g(t) * g(t) \equiv \int_{-\infty}^{\infty} g(\tau)g(t + \tau)d\tau \approx \delta(t). \quad (8.6)$$

PRBS are sequences having the property of a delta-like autocorrelation. These sequences are used in multiple transmitter and receiver systems. They are of length $m = 2^l - 1$, for $l$ being a positive integer. As mentioned before the cyclic or circular autocorrelation of a sequence is delta-like, which can be seen in Figure 8.4. The cross-correlation of two different sequences is zero everywhere. The sequences are generated by deterministic algorithms (Topuzoğlu & Winterhof 2006) and resemble similar properties as random sequences. However they are not
8.3 CW lidar simulations for the ELT

In an AO system a small fraction of the LGS photons pass the beam splitter and are not directed toward the wavefront sensor. By using a notch filter these photons could be extracted from the signal that is being directed towards the science camera. In the setup of an ELT, these photons could be used for retrieving sodium density profiles, if the intensity of one or more
LGS were modulated. To check the feasibility of this approach, numerical simulations were carried out. The numerical simulations assumed a telescope of the size of the ELT, observing at zenith. The system was assumed to be photon-noise limited. The laser is assumed to be continuously modulated by a repeated PRBS. In addition to the simulations, P. Hickson made an analytical derivation of the accuracy of the method. The estimated centroid error is given by (J.A. Hellemeier, D. Bonaccini Calia, P. Hickson, A. Otarola, T. Pfrommer, MNRAS paper in preparation)

\[
\sigma_z \simeq \frac{2 - \epsilon}{\epsilon} \sqrt{\frac{n}{12N_\gamma}} Z,
\]  

(8.7)

where \( \epsilon \) is the modulation strength. \( N_\gamma \) is the total number of detected photons and depends on the total integration time and modulation strength. \( Z \) is the altitude interval used for calculating the sodium density centroid. \( n \) is the number of altitude bins in the interval \( Z \) and depends on the sampling rate. The estimated centroid error decreases with decreasing \( n \). However, the sampling rate needs to be large enough to prevent undersampling and aliasing. Since \( N_\gamma \) is proportional to \( 1 - \epsilon/2 \), for the centroid error the following relation holds

\[
\sigma_z \propto \frac{1}{\epsilon} \sqrt{1 - \epsilon/2}.
\]  

(8.8)

The simulations had modulation strength, integration time, PRBS length and sampling rate as input parameters. A sample profile resembling the profiles obtained in the experiment at the LZT was used for the sodium layer. The LGS was assumed to be of 7th-magnitude, with a return flux of \( 15.8 \times 10^6 \) photons m\(^{-2}\) s\(^{-1}\) at the primary mirror. The product of telescope throughput and quantum efficiency was assumed to be 0.3 and it was assumed that 3% of the LGS photons pass the beamsplitter. The LGS return flux, without noise, was calculated by the convolution of the modulated laser intensity and the sodium density distribution (Equation 8.4). The photon noise for a given time interval was simulated by drawing a random number from a Poisson-distribution having the mean of the noiseless return flux in that time interval. An example showing noiseless and noise-added return flux and the resulting sodium density profile can be seen in Figure 8.5.

For each set of parameters 1000 sodium density profiles were simulated. The RMS centroid error was determined for the set of parameters, from the centroids of the obtained profiles and the centroid of the truth profile. The results are shown in Figure 8.6 and Figure 8.7. The
Figure 8.5: top: Simulated return flux with and without noise. bottom: The retrieved sodium density profiles from the signals shown above and the truth profile.
8.3. CW lidar simulations for the ELT

Figure 8.6: RMS centroid error vs PRBS length for an integration time of 3 s.

results agree with the predicted centroid error from Equation 8.7. The centroid error does not depend on PRBS length, but on modulation strength, sampling rate and the total number of photons. For the ELT, a centroid error smaller than 20 m can be accomplished by modulation strength greater than 30% for an integration time of 3 s.

The performance of the method depends on zenith angle $\zeta$, since total number of photons $N_\gamma$, the altitude interval $Z$ and the line-of-sight centroid $\hat{z}$ depend on airmass $X \simeq \sec \zeta$. From geometry it follows that $Z$ and $\hat{z}$ are proportional to $X$. If $Z$ increases by a factor of $X$ and the sampling rate is kept constant, the number of samples $n$ increases by a factor of $X$, as well. The total number of photons is proportional to $X \exp(-0.921kX)$, where $k$ is the extinction coefficient of the atmosphere at 589 nm. The factor 0.921 is a result of the definition magnitude and is more accurately $2.5/\ln(10)$. A typical value of $k$ is 0.162 which is the extinction coefficient for 550 nm at the Kirtland Air Force Base near Albuquerque\footnote{Extinction coefficients may vary with altitude, aerosol content and other parameters. The value stated is the best estimate to be found in literature for the sodium $D_2$-line.} (Drummond et al. 2004). For the estimated centroid error and the wavefront error from Equations 8.1 and 8.7 the following relations can be found.
8.3. CW lidar simulations for the ELT

Figure 8.7: RMS centroid error for different integration times. The simulated data agree well with the predicted error (dashed line).

\[ \sigma_\hat{z} \propto X \exp(0.460kX), \]
\[ \sigma_{WF} \propto X^{-1} \exp(0.460kX). \]  

(8.9)

The wavefront error decreases for decreasing airmass for \( X < 14.5 \). So employing the CW lidar method at zenith results in the highest wavefront error. Results for the wavefront error for different pointing elevations for the ELT, the TMT and the GMT are shown in Figures 8.8 - 8.10. For the TMT and GMT, PRBS modulation of 50\% and an integration time of 10 seconds could achieve wavefront errors below 30 nm, even when observing at zenith. 12 nm is the TMT error budget for sodium centroid variation. For the ELT it is more difficult to obtain small wavefront errors, since the ELT is larger and the wavefront error increases for increasing aperture size, despite the increasing photon collecting area.

The method could be improved by using all LGS in an AO system. The horizontal structure function of the sodium density profile only varies slightly for an angular separation typical for
multiple LGS systems\textsuperscript{10}. The GMT and ELT will use six LGS, in the AO systems. The TMT will use six LGS when run in multi-conjugate AO mode and eight LGS when run in multi-object AO mode. The wavefront error from the CW lidar method with six LGS for observations at zenith for the three extremely-large telescopes is shown in Figure 8.11. Compared to the case of one LGS being modulated the wavefront will decrease by a factor of $1/\sqrt{6}$ when the modulation is applied to all six LGS. For observations at zenith it is possible to keep the wave-front error below 30 nm for integration times lasting 5 seconds or longer at modulation depth of 0.3 or higher. For the ELT it is possible to keep the wave-front error below 50 nm for the same modulation parameters.

\textsuperscript{10}For a separation of 30 arcsec the typical root mean square change of the centroid was found to be on the order of 45 m (P. Hickson, private communication).
8.4 Experimental results

In the summer of 2014, an experiment at the LZT was carried out by D. Bonaccini Calia, P. Hickson and T. Pfrommer to test the method. The ESO Wendelstein CW laser was brought to the LZT. In the experiment profiles obtained by the CW laser and the short-pulsed lidar of the LZT, were compared. The profiles obtained by the LZT lidar system serve as truth profiles for assessing the accuracy of the profiles obtained by the CW laser. The LZT lidar system used a Nd:YAG pumped dye laser, having a power of 4 – 5 W and a pulse length of 6 ns. The Wendelstein CW laser is a Raman-fibre laser with a maximum output of 20 W. Both lasers were tuned to the sodium D\textsubscript{2a}-line. For the CW laser 10\% of the laser power was used for repumping of the D\textsubscript{2a}-line. The lidar laser and CW laser ran alternately, the CW laser filling the intervals between lidar pulses. The lidar laser emitted 6-ns pulses. To allow sufficient time for the backscatter from the lidar to arrive, 1 ms after a lidar pulse the CW laser was enabled. A single PRBS modulation ran for about 10 ms and thereafter the CW laser was enabled.

Figure 8.9: Predicted wavefront error for ELT, TMT and GMT for observations at 20° zenith angle.
laser was disabled again. This setup prevented the backscattered light from lidar laser and CW laser from overlapping in time. The return signal from the sodium layer was measured by the LZT, using an avalanche photo-diode (APD) operating in analog mode. In front of the APD a narrow-band filter was employed to reduce background light. The central frequency of the filter is 600 nm with a half-power bandwidth of 25 nm. For amplification of the signal, a current amplifier was used, then a digitizer converted the signal at a rate of 16.6 MHz. Careful attention was paid to grounding and shielding the electronics. A 1-MHz-3-db cutoff filter was applied at the digitizer input. Still, the received signal was affected by noise in the range of 20 to 100 kHz, the noise most-likely emerging from radio-interference. During the experiment the CW laser was modulated with 50% and 67.5% modulation strength. The modulation frequency was 1 MHz and the PRBS used had a length of $2^{13} - 1 = 8191$. The experiment took place in July 2014. Due to cirrus clouds, only the data of the night of 17th of July were useful and are being presented here. An overview of the data is given in Table 8.1.
8.4. Experimental results

Figure 8.11: Predicted wavefront error for ELT, TMT and GMT for observations at zenith with 6 LGS being used for the CW lidar method.

8.4.1 Data reduction

The APD yielded an reversed signal, which was first inverted. For the signal of the lidar the background was then subtracted by fitting a sixth-order polynomial to the altitude range 75-140 km. The interval containing the sodium profile was selected and the background was extrapolated by a linear function between the values of the sixth-order polynomial at the start and end point of the interval. This technique is similar to that used in spectroscopy, where distinct peaks are left out and the continuum underlying the peak is extrapolated by a linear function.

Table 8.1: Observation details

<table>
<thead>
<tr>
<th>date (UTC)</th>
<th>start time (UTC)</th>
<th>end time (UTC)</th>
<th>AOM</th>
<th>PRBS sampling rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 Jul</td>
<td>06:26</td>
<td>07:58</td>
<td>67.5%</td>
<td>1 MHz</td>
</tr>
<tr>
<td>17 Jul</td>
<td>09:14</td>
<td>09:48</td>
<td>50.0%</td>
<td>1 MHz</td>
</tr>
</tbody>
</table>
8.4. Experimental results

Figure 8.12: Example of the cross-correlation of the CW signal with the PRBS. The distinct peak originates from Rayleigh-backscattering, the smaller peak on the right of it from the sodium fluorescence.

The background was subtracted to obtain the final lidar profile. To reduce noise, the signal of the CW laser was smoothed with a Savitzky-Golay filter (Savitzky & Golay 1964). The filter fits a low-order polynomial to a small data sub-set. In this case a third-order polynomial was fit to the data contained in a 3-μs-window. After the cross-correlation with the PRBS was executed, a seventh-order polynomial was fit to the same altitude interval used for the lidar. The background underlying the sodium layer was again extrapolated by a linear function. The cross-correlation of the signal and the PRBS can be seen in Figure 8.12. The most distinct peak originates from Rayleigh-scattering, but the smaller peak from the sodium return flux is also significant.

The lidar profiles are averages corresponding to profiles obtained from 127 laser pulses. The profiles for the CW lidar method were averaged over 127 sequences which correspond to an integration time of 1 second. Since there was jitter in the time shift between the lidar pulse and the start of the CW laser sequence, there was a small random altitude shift for the CW profiles. This altitude shift was corrected for by minimizing the second moment of the difference of lidar and a shifted CW profile. The maximum altitude shift allowed was 900 m. The remaining CW
8.4. Experimental results

Figure 8.13: Comparison of a lidar (solid) and CW (dotted) profile. The dashed line shows the CW profile obtained by averaging over a period of 10 seconds.

Profiles were still affected by noise. By averaging the CW profiles within \( \pm 5 \) seconds additional noise cancelling was applied. All profiles were normalized to unit area. Figure 8.13 shows the comparison of 1-s averaged lidar profile, 1-s averaged CW profile and 10-s averaged CW profile. The period of 10 seconds appears to be long enough to cancel low-frequency noise components, but short enough for sodium density structure variations to not have a significant impact.

In Pfrommer & Hickson (2014) four key measures are introduced to describe sodium profiles. These quantities are the centroid altitude \( \hat{z} \), the square root of the second moment \( \nu \), the width of enclosed energy \( w \) and the width of a specified flux threshold \( \xi \). These measures indicate differences in the characteristics of the obtained profiles. In the following they are used to compare the estimated sodium profiles from the CW method with the ‘truth’ profiles obtained by the lidar system. The width of enclosed energy yields the width interval which encloses a set fraction of the integrated flux. Since the signal was affected by noise, the fraction of enclosed energy was set to 80\%. The width of the specified flux threshold yields the width where the flux exceeds a set threshold of the maximum flux. The flux threshold was set to 20\%. 
Table 8.2: Parameters for the Gaussian distributions.

<table>
<thead>
<tr>
<th>parameter</th>
<th>AOM</th>
<th>Ω̂z</th>
<th>Ω̂µ</th>
<th>Ωw</th>
<th>Ωξ</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ [m]</td>
<td>50.0%</td>
<td>-23.73</td>
<td>12.01</td>
<td>113.19</td>
<td>482.81</td>
</tr>
<tr>
<td>µ [m]</td>
<td>67.5%</td>
<td>83.76</td>
<td>-3.75</td>
<td>98.78</td>
<td>-134.43</td>
</tr>
<tr>
<td>σ [m]</td>
<td>50.0%</td>
<td>202.88</td>
<td>54.75</td>
<td>560.13</td>
<td>787.36</td>
</tr>
<tr>
<td>σ [m]</td>
<td>67.5%</td>
<td>176.09</td>
<td>80.44</td>
<td>331.24</td>
<td>432.50</td>
</tr>
</tbody>
</table>

8.4.2 Results

In total, 882 profiles were obtained and compared. Two different modulation strengths were used for comparison. 204 profiles were recorded with a modulation strength of 67.5% and 678 with a modulation strength of 50%. For the comparison the flux-weighted profiles were used. In contrast to density-weighted profiles, flux-weighted profiles are not corrected for geometrical effects decreasing the flux from higher sodium layers. AO systems do not correct for the geometrical effects and use flux-weighted profiles. CW profiles and lidar profiles have been compared by calculating the differences of the measures centroid ̂z, second moment ̂µ, width of enclosed energy ̂w and width of a specified flux threshold ̂ξ. The lidar measure yields the 'truth' measure ̂xl. The offset Ω is then calculated by subtracting the truth measure from the measure ̂xcw obtained from the CW profile

\[ \Omega = ̂xcw - ̂xl. \] (8.10)

The results for the offsets of all profiles are shown in histograms in Figure 8.14 and Figure 8.15. The distributions in the histograms were fitted with gaussian distributions by least-square fits. The mean µ and the standard deviation σ for the gaussian distributions can be found in Table 8.2.

The standard deviations for the distribution of the centroids are 176.1 m for 67.5% AOM and 202.9m for 50% AOM. The second moments of the profiles typically are about 4 km. The standard deviation for their distribution range between 50 – 100 m. The standard deviation for enclosed energy and flux threshold exceed the standard deviation for the second moment by almost one magnitude. Typically the widths of enclosed energy and flux threshold are about 10 km.
8.4. Experimental results

Figure 8.14: Distribution of the differences of the centroid altitudes of the CW and lidar profiles \( (above) \). Distribution of the differences of the second moments of the profiles \( (below) \).
8.4. Experimental results

Figure 8.15: Above: Distribution of the differences of the widths of 80% included energy. Below: Distribution of the differences of the widths exceeding 20% of the maximum flux.
8.5 Discussion

The results from the experiment at the LZT show that PRBS amplitude modulation of a CW laser can be used to retrieve sodium density profiles. The centroid offset, on average, is within 200 m. However, in the experiment, the photon-noise limited accuracy predicted by theory could not be reached. The results are diminished by radio-frequency noise and instrumentation effects. Still, to our knowledge, these sodium density profiles obtained by PRBS modulation are unmatched in spatial resolution.

Numerical simulations are in agreement with the theoretically-predicted accuracy limited by photon-noise. In AO systems of ELTs the method could be beneficial. The small percentage of LGS light leaking out of the optical path could be used to retrieve sodium density profiles from one or more LGS. For the ELT 50% PRBS modulation of one LGS for an integration time of ten seconds is sufficient to limit the wavefront error within 50 nm. In an approach where all LGS of the AO systems are used, a profile could be retrieved every five seconds for modulation strength of 0.2-0.4. For these modulation strengths the average LGS return flux decreases by 10-20%. For the TMT, a modulation of six LGS at a modulation strength of 0.5 would be needed to match a wavefront error of 12 nm. A modulation strength of 0.5 corresponds to a decrease of 25% in LGS return flux. For observations in the infrared in typical atmospheric conditions LGS return flux exceeds the needed flux by a factor of two. Hence, LGS flux margins would allow for a decrease of this amount without significant losses in system performance.

The wave-front errors shown are the centroid errors from the PRBS method transformed into wavefront-errors. The wave-front error if a NGS and amplitude-modulated LGS were used would be different. Analysis of the wave-front error in a system, where a NGS and amplitude-modulated LGS are used, is complicated. The CW lidar method could allow for longer integration times for the NGS which would permit the use of fainter NGS, thereby increasing the sky coverage. Knowledge of the sodium density profile would not only be used in centroiding algorithms, it could boost the performance in wavefront reconstruction of matched-filter algorithms. As a next step, we will analyze the possible gain in performance for matched-filter algorithms and the level of accuracy obtainable.
Chapter 9

Conclusions and future work

This thesis deals with site testing and techniques for improvement of AO system performance. Meteorological grid data for fifteen observatory sites and two campaigns of turbulence profiling with scintillometers have been presented. The technique of polarization modulation for LGS return-flux enhancement has been studied in an experiment at the Observatorio Roque de la Muchachos on La Palma. Results for a CW lidar technique for retrieving sodium density profiles, and a performance estimate for this technique applied to extremely-large telescopes have been presented.

The ATP was installed at Ali Observatory in May 2018. By the time of writing of this thesis, it has been collecting data for over one year. The data analysis is in progress. First preliminary results look promising, but it is still too early to draw final conclusions. We are planning on comparing the obtained data with data from a DIMM installed at Ali. ERA-5 wind speed data are available and will be used to investigate correlations between the ground layer seeing and local weather trends. The PTP was brought to Colombia in December 2018. Although it is not in operation yet, the arrival of the PTP has created momentum for the project, and will soon be put to good use. There are plans to clone the instrument for testing multiple sites. Our collaborators have been trained in operating the instrument and analyzing the data. They are looking for suitable sites for a solar telescope which could then be studied with multiple instruments.

Polarization modulation has been studied at the Observatorio Roque de la Muchachos on La Palma. A receiver system for the experiment has been designed and built at UBC. The experiment took place in two phases, the first phase in July 2017. At that time only the amplitude (not the polarization) was modulated, showing that the Larmor frequency could be determined with our experimental setup, and from that the geomagnetic field strength was found. Besides being an important stepping stone towards polarization modulation, the results of the first phase proved useful our setup as a magnetometer for the mesosphere. The enhancement in
Chapter 9. Conclusions and future work

LGS return flux was 18% in the first phase. In the second phase of the experiment, in April 2018, when polarization modulation was applied, an LGS return flux enhancement of 6% was found. This does not completely reveal the potential of the polarization modulation technique for AO systems, since for AO the enhancement of modulation versus no-modulation is important. At the moment we are discussing whether we should have another campaign to address this question. In that event, we could attempt to detect the magnetic anomaly around the Canary islands. Magnetic anomalies are caused by subsurface structure variations in the Earth’s crust and often occur in volcanic regions. The technique could also be used to study the effect of charged particles entering the atmosphere in polar regions. It is assumed that the particles causing auroras have an impact on the magnetic field in the upper atmosphere, but the effect of the particles entering on the magnetic field in the mesosphere has not yet been studied. With the magnetometry technique presented in this thesis it is possible to monitor Earth’s magnetic field in the mesosphere and the effect of the solar wind on the magnetic field in the mesosphere could be studied.

The CW lidar method shows potential for integration with AO systems on ELTs. It could be used to detect sodium centroid variations which at the moment are inaccurately interpreted as atmospheric focus changes by the LGS control loop. Our results show that centroid variations could be detected to an accuracy matching the wave-front error budgets of the TMT and ELT. To completely assess the feasibility of the method, a system using NGS and modulated LGS for focus correction should be analyzed. In addition, the performance increase for wavefront sensing with matched filter algorithms, having updated estimates of the sodium density profile, should be analyzed. The NGS control loop is run at about 100 Hz for focus sensing. On ELT’s, the CW lidar method could provide a centroid measurement with sufficient accuracy at 0.1 Hz. While it might not be possible to remove the need for fast focus correction from NGS the CW lidar method could yield profiles to improve the performance of AO systems using matched-filter algorithms.
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Appendix A

Tables from Chapter 3
### Table A.1: Cloud-cover fraction $f_c$

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146
### Table A.3: Precipitable water vapour in kg/m²

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### Table A.4: Vertical wind velocity in cm/s

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