

Astronomical seeing conditions as determined by turbulence modelling and optical measurement

by

Marisa Nickola

Submitted in partial fulfilment of the requirements for the degree

MASTER OF SCIENCE

in the Faculty of Natural & Agricultural Sciences

University of Pretoria

Pretoria

South Africa

November 2012

Astronomical seeing conditions as determined by turbulence modelling and optical measurement

Author: Nickola Marisa
Promoter: Prof. George Djolov¹ and
Prof. Ludwig Combrinck^{1,2}
Department: ¹Department of Geography, Geoinformatics and Meteorology,
University of Pretoria, Pretoria 0002, South Africa
²Hartebeesthoek Radio Astronomy Observatory (HartRAO),
P.O. Box 443, Krugersdorp 1740, South Africa
Degree: Master of Science

Abstract

Modern space geodetic techniques are required to provide measurements of millimetre-level accuracy. A new fundamental space geodetic observatory for South Africa has been proposed. It will house state-of-the-art equipment in a location that guarantees optimal scientific output. Lunar Laser Ranging (LLR) is one of the space geodetic techniques to be hosted on-site. This technique requires optical (or so-called astronomical) seeing conditions, which allow for the propagation of a laser beam through the atmosphere without excessive beam degradation. The seeing must be at ~ 1 arc second resolution level for LLR to deliver usable ranging data. To establish the LLR system at the most suitable site and most suitable on-site location, site characterisation should include a description of the optical seeing conditions. Atmospheric turbulence in the planetary boundary layer (PBL) contributes significantly to the degradation of optical seeing quality. To evaluate astronomical seeing conditions at a site, a two-sided approach is considered – on the one hand, the use of a turbulence-resolving numerical model, the Large Eddy Simulation NERSC (Nansen Environmental and Remote Sensing Centre) Improved Code (LESNIC) to simulate seeing results, while, on the other hand, obtaining quantitative seeing measurements with a seeing monitor that has been developed in-house.

Keywords: optical turbulence, astronomical seeing, large eddy simulation, seeing monitor, Lunar Laser Ranging (LLR).

List of Publications

The following contributions have been published in peer review journals or proceedings as part of this work or related to it.

1. **Nickola, M.**, Botha, R.C., Esau, I. and Djolov, G.D. and Combrinck, W.L. 2011. Site characterisation: astronomical seeing from a turbulence-resolving model. *South African Journal of Geology*, **114**(3-4): 581-584.
2. **Nickola, M.**, Esau, I. and Djolov, G. 2010. Determining astronomical seeing conditions at Matjiesfontein by optical and turbulence methods. *IOP Conference Series: Earth and Environmental Science*, **13**(1): 012010.
3. **Nickola, M.**, Botha, R. and Combrinck, W.L. 2009. Investigation of techniques to determine astronomical seeing conditions at Matjiesfontein. *Proceedings of the South African Geophysical Association 2009 Biennial Technical Meeting and Exhibition "Ancient rocks to modern techniques"*. Swaziland, 16-18 September 2009: 598-602.

Declaration

I, Marisa Nickola, hereby declare that the work on which this thesis is based, which I hereby submit for the degree Master of Science, Faculty of Natural and Agricultural Sciences at the University of Pretoria, is my own work except where acknowledgements indicate otherwise. This work has not previously been submitted by me for another degree at this or any other tertiary institution.

.....

November 2012

Acknowledgements

This thesis is the result of research I carried out at the Hartebeesthoek Radio Astronomy Observatory under the Space Geodesy programme while registered at the University of Pretoria.

I would like to thank the following people and institutions for their assistance with the research:

- Prof George Djolov, Prof Ludwig Combrinck, Roelf Botha and Dr Igor Esau
- Hartebeesthoek Radio Astronomy Observatory (HartRAO) and especially Glenda Coetzer, Christina Botai and Sarah Buchner
- University of Pretoria and especially Prof Hannes Rautenbach, Ingrid Booyen, Corné van Aardt and fellow-student, Philbert Luhunga
- G.C. Rieber Climate Institute at the Nansen Environmental and Remote Sensing Center (NERSC)
- Inkaba yeAfrica and especially Elronah Smit
- Dr Stoffel Fourie and the people of Matjiesfontein
- South African Astronomical Observatory (SAAO) and especially Laure Catala, Dr David Buckley, Dr Steve Crawford and Dr Timothy Pickering
- Dr Aziz Ziad and Yan Fantei-Caujolle from the University of Nice
- The South African Weather Service (SAWS) and especially Colleen de Villiers and Dr Jan Gertenbach
- Roelof Burger from the Climatological Research Group at the University of the Witwatersrand (Wits)
- Jaco Mentz, Prof Johan van der Walt, Prof Pieter Meintjies and Willie Koorts
- Johan Posthumus and Gerda Herne from Promethium Carbon Pty Ltd
- Eric Aristidi, Eric Fossat, Hubert Galleé, Florent Losse, Andreas Muschinski, Andrea Pelligrini, Tony Iaccarino, Tatanya Sadibekova and Mark Swain
- Gerhard Koekemoer, Wayne Mitchell, Johan Smit, Oleg Toumilovitch and Andrie van der Linde
- Mike Cameron
- Leslie Nickola as well as Golda and Tewie Muller

Table of Contents

Astronomical seeing conditions as determined by turbulence and optical methods	i
Abstract.....	ii
List of publications	iii
Declaration.....	iv
Acknowledgements	v
Table of Contents	vi
List of Tables.....	viii
List of Figures.....	ix
List of Abbreviations and Acronyms	xi
1. Introduction	1
1.1. Background	1
1.1.1. Space geodesy	1
1.1.2. Lunar Laser Ranging	3
1.1.3. The need for a new fundamental space geodetic observatory	4
1.1.4. Astronomical seeing determined from turbulence and optical methods	7
1.2. Motivation for the research.....	8
1.3. Aim and objectives of the research.....	8
1.4. Method	9
1.5. Study outline	11
2. Theoretical background to seeing.....	12
2.1. Introduction	12
2.2. Atmospheric turbulence	12
2.2.1. Earth's atmosphere	12
2.2.2. Turbulence theory.....	16
2.2.3. Index of refraction structure parameter, C_N^2	19
2.3. Astronomical seeing.....	21
2.3.1. Diffraction limit of telescope.....	23
2.3.2. Fried parameter.....	25
2.4. Link between atmospheric turbulence and astronomical seeing.....	26
3. Methodology.....	28
3.1. Introduction.....	28
3.2. Modelling seeing by turbulence method.....	28
3.2.1. Large Eddy Simulation (LES)	29
3.2.2. The LES NERSC Improved Code (LESNIC) and DATABASE64	30
3.2.3. Turbulence method – LESNIC modelling	31
3.3. Measuring seeing by optical method	35
3.3.1. Point Spread Function (PSF).....	35
3.3.2. Image scale	36
3.3.3. Sampling.....	36
3.3.4. Experimental method.....	37
4. Seeing monitor - proposed design	40
4.1. Introduction.....	40
4.2. Hardware requirements.....	40
4.2.1. Telescope.....	42
4.2.2. CCD camera	42
4.2.3. Mount	44
4.3. Hardware selection	45
4.3.1. Telescope.....	45
4.3.2. CCD camera	48

4.3.3. Mount	52
4.4. Software and automation	54
4.5. Logistical issues	55
4.6. Target instrumentation	56
5. Results and discussion	58
5.1. Introduction	58
5.2. Turbulence method	58
5.2.1. Preliminary results using LESNIC	58
5.2.2. Results published in literature	60
5.2.3. Comparison of simulated and published results	63
5.3. Optical method	68
5.3.1. PSF seeing experiment: calibration results using α Cen binary	69
5.3.2. PSF seeing experiment: initial results with α CenA	72
6. Combination of methods	75
6.1. Introduction	75
6.2. Proposed two-sided approach	75
7. Conclusion	78
7.1. Summary	78
7.2. LESNIC	78
7.3. Seeing monitor	79
7.4. Combination of methods	81
References	83
Appendix A1	91
Appendix A2	96
Appendix A3	102
Appendix A4	104

List of Tables

Table 4.1. Comparison of commercially available telescope OTAs.	46
Table 4.2. Dawes' limit for specific telescope aperture sizes and FOV/pixel for various CCD camera / telescope aperture combinations.	48
Table 4.3. Comparison of CCD cameras appearing in Table 4.2.	49
Table 4.4. Comparison of telescope mount.	53
Table 5.1. Fried parameter value and seeing for the first eight runs in DB64.	60
Table 5.2. PSF seeing experiment: verification of seeing monitor setup by observing binary star separation.	71
Table 5.3. PSF seeing experiment: initial seeing results at Matjiesfontein with α CenA.	74
Table A4.1. Comparison of various seeing techniques / instruments.	105

List of Figures

Figure 1.1. Location of LLR targets on the Moon.....	3
Figure 1.2. A retro-reflector array on the Moon’s surface.	3
Figure 1.3. Space geodesy at HartRAO – VLBI, GNSS, DORIS (Marion Island) and SLR MOBLAS-6).	5
Figure 1.4. The OCA 1-m aperture Cassegrain telescope mount and tube at HartRAO.....	6
Figure 2.1. Temperature profile in the atmosphere.	13
Figure 2.2. Planetary boundary layer (PBL).	14
Figure 2.3. The PBL regions.	15
Figure 2.4. Kolmogorov model of turbulence.	16
Figure 2.5. Degradation of image quality by turbulence.	22
Figure 2.6. Diffraction pattern of star image through a telescope and profile of image brightness.	23
Figure 3.1. LES – large eddies solved for, small eddies filtered out and modelled.	30
Figure 3.2. LESNIC provides a database of turbulence-resolving simulations, called DATABASE64.	31
Figure 3.3. Seeing from ϵ_θ , $\epsilon^{-1/3}$, P and T from DATABASE64.	34
Figure 3.4. Example of a star’s intensity profile or Point Spread Function (PSF).....	35
Figure 3.5. Full Width at Half Maximum (FWHM) of a Gaussian distribution.	37
Figure 3.6. Diagrammatic representation of seeing analysis process.....	37
Figure 3.7. Binary stars: overlapping Airy discs.	39
Figure 4.1. Graph depicting possible telescope and camera combinations.	41
Figure 4.2. Recently acquired second-hand 14" Meade LX200 GPS SCT with alt-az fork- arm mount and field tripod.	47
Figure 4.3. The Point Grey Grasshopper GRAS-03K2M (for DIMM measurements) and GRAS-20S4M (for PSF seeing monitor measurements) CCD cameras.	50
Figure 4.4. The Philips ToUcam Pro II PCVC840K webcam with lens removed and replaced by MOGG adapter.	51
Figure 4.5. Test setup for double star observation – 10" Meade LX200 SCT, ToUcam webcam and laptop.	51
Figure 4.6. The Orion StarShoot USB Live View Value Kit with imaging flip mirror and StarShoot USB eyepiece.	51

Figure 4.7. The Cerro Tololo Inter- American Observatory (CTIO) RoboDIMM in Chile with motorised canvas clamshell enclosure.	56
Figure 4.8. The Isaac Newton Group of Telescopes (ING) – Instituto de Astrofísica de Canarias (IAC) RoboDIMM with Astro Haven fibreglass clamshell at the Observatorio del Roque de los Muchachos (ORM), La Palma, Canary Islands.	56
Figure 5.1. The simulated $C_N^2(h)$ and $C_T^2(h)$ log profiles for runs 1 to 8.	59
Figure 5.2. The observed $C_N^2(h)$ profiles obtained during site testing at Dome C in Antarctica.	62
Figure 5.3. The $C_N^2(h)$ linear profile and LESNIC external control parameters for runs 1 to 8.	64
Figure 5.4. Flight Vol 563 $C_N^2(h)$ profile measured at Dome C, Antarctica.	67
Figure 5.5. LESNIC-modelled $C_N^2(h)$ profile for run 8 from DB64.	67
Figure 5.6. Separation of binary stars.	70
Figure 5.7. Intensity profile of binary star principal component.	72
Figure 5.8. Bell-shaped Gaussian distribution curve.	73
Figure 6.1. Comparison of modelled and measured Fried and seeing parameter results.	77
Figure A1.1. Potential sites for a new fundamental space geodetic observatory (and the climatic regions of South Africa in which they are located).	91
Figure A1.2. Panoramic view – Matjiesfontein site.	93
Figure A1.3. Matjiesfontein site – looking north towards proposed LLR location on ridge; on-site Davis Vantage Pro2 Automatic Weather Station (AWS); looking southeast from the LLR ridge down into the valley.	93
Figure A4.1. DIMM mask with wedge prism.	108
Figure A4.2. The SALT MASS-DIMM in operation at the SAAO site in Sutherland with the MASS-DIMM instrument attached at the exit pupil.	111
Figure A4.3. The GSM at Sutherland operated in DIMM mode with the two Maksutov telescopes sharing the same mount.	113
Figure A4.4. The PBL setup at Sutherland with SALT in the background.	114
Figure A4.5. The PBL’s optical module includes a PixelFly CCD camera.	114
Figure A4.6. The Boltwood Cloud Sensor at HartRAO.	116
Figure A4.7. The SAAO All Sky Camera at Sutherland is located together with the SALT MASS-DIMM in the ox wagon enclosure.	116

List of Abbreviations and Acronyms

AA	: Angle of Arrival
AC	: Achromatic
A/D	: Analogue to Digital
ADC	: Analogue-to-Digital Conversion
AGAP	: Astronomy Geographic Advantage Protection
alt-az	: altitude-azimuth
APO	: Apochromatic
APOLLO	: Apache Point Lunar Laser-ranging Operation
AWS	: Automatic Weather Station
C-BASS	: C-Band All Sky Survey
CCD	: Charge-Coupled Device
CFL	: Courant-Fridrihs-Levi
CO-SLIDAR	: COupled SLodar scIDAR
CRF	: Celestial Reference Frame
CTIO	: Cerro Tololo Inter-American Observatory
D/A	: Digital to Analogue
DB64	: DATABASE64
DC	: Direct Current
Dec	: Declination
DIMM	: Differential Image Motion Monitor
DNS	: Direct Numerical Simulation
Dobs	: Dobsonian
DORIS	: Doppler Orbitography and Radiopositioning Integrated by Satellite
EOP	: Earth Orientation Parameters
FF	: Full-Frame
FL	: Focal Length
FOV	: Field Of View
FWC	: Full-Well Capacity
FWHM	: Full Width at Half Maximum
G-SCIDAR	: Generalised SCIDAR
GE	: German Equatorial
GEM	: German Equatorial Mount
GNSS	: Global Navigation Satellite System

GPS	: Global Positioning Satellite
GSM	: Generalized Seeing Monitor
GUI	: Graphical User Interface
HartRAO	: Hartebeesthoek Radio Astronomy Observatory
HVR-GS	: High Vertical Resolution G-SCIDAR
IAC	: Instituto de Astrofisica de Canarias
IEEE	: Institute of Electrical and Electronics Engineering
IL	: InterLine
ING	: Isaac Newton Group of Telescopes
IPEV	: Institut Polaire Français Paul Emile Victor
KAT	: Karoo Array Telescope
LES	: Large Eddy Simulation
LESNIC	: Large Eddy Simulation NERSC Improved Code
LLR	: Lunar Laser Ranging
LOLAS	: Low Layer SCIDAR
LuSci	: Lunar Scintillometer
M-N	: Maksutov-Newtonian
MASS-DIMM	: Multi-Aperture Scintillation Sensor - Differential Image Motion Monitor
MeerKAT	: Karoo Array Telescope (larger array)
MLRO	: Matera Laser Ranging Observatory
MLRS	: McDonald Laser Ranging Station
NERSC	: Nansen Environmental and Remote Sensing Center
ORM	: Observatorio del Roque de los Muchachos
OCA	: Observatoire de la Côte d'Azur
OS	: Operating System
OTA	: Optical Tube Assembly
PBL	: Planetary Boundary Layer
PBL	: Profileur Bord Lunaire (or Lunar Limb Profiler)
PE	: Periodic Error
PEC	: Periodic Error Correction
PMT	: Photo-Multiplier Tube
PNRA	: Programma Nazionale di Ricerche in Antartide
PPEC	: Permanent Periodic Error Correction

PSF	: Point Spread Function
RA	: Right Ascension
RANS	: Reynolds-Averaged Navier-Stokes
RC	: Ritchey-Chrétien
RFI	: Radio Frequency Interference
RH	: Relative Humidity
S/LLR	: Satellite/Lunar Laser Ranging
S-N	: Schmidt-Newtonian
SAAO	: South African Astronomical Observatory
SALT	: South African Large Telescope
SAWS	: South African Weather Service
SBL	: Stably stratified planetary Boundary Layer
SCIDAR	: SCIntillation Detection And Ranging
SCT	: Schmidt-Cassegrain Telescope
SHABAR	: SHAdow BAnd Ranging
SI	: Scintillation Indice
SKA	: Square Kilometre Array
SLODAR	: SLOpe Detection And Ranging
SLR	: Satellite Laser Ranging
SNODAR	: Surface layer NOn-Doppler Acoustic Radar
SODAR	: SOnic Detection And Ranging
TRF	: Terrestrial Reference Frame
USB	: Universal Serial Bus
VLBI	: Very Long Baseline Interferometry
WF	: Weighting Function