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Determining astronomical seeing conditions at Matjiesfontein by optical and turbulence methods

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Abstract. Matjiesfontein in the Karoo has been proposed as a suitable location for a new fundamental space geodetic observatory. On-site geodetic equipment will include a Lunar Laser Ranger (LLR). LLR requires sub-arcsecond optical seeing conditions for delivery of high quality and quantity data. Seeing conditions at the Matjiesfontein site will be evaluated by making use of an automated seeing monitor and by modelling atmospheric turbulence with Large Eddy Simulation Nansen Center Improved Code (LESNIC).

Introduction

The Space Geodesy Programme operates from the HartRAO site where geodetic data quality and quantity are adversely affected by pollution, RFI (Radio Frequency Interference), cloud cover and obsolete instrumentation. A new fundamental space geodetic observatory at a new site with new equipment has been proposed. A geotechnical survey has identified a site just 4 km south of Matjiesfontein in the Karoo as suitable for optimal scientific output.

An S/LLR (Satellite / Lunar Laser Ranging) system is to be a major addition to the equipment to be located at the new space geodetic observatory. Because of single-photon returns, LLR requires optimal optical seeing conditions, which will allow for the propagation of a laser beam through the atmosphere without excessive beam degradation. A site suitable for LLR must deliver seeing of ~1 arc-sec for the LLR to achieve millimetre-level accuracy in ranging to the Moon. [1]

Figure 1. Matjiesfontein site – looking north towards proposed LLR location on ridge.

Figure 2. On-site Vantage Pro 2 weather station.

Figure 3. Matjiesfontein site – looking southeast from LLR ridge down into valley.

Seeing

A star is located at an immense distance from the Earth and should appear as a point source when observed through a telescope (or by the naked eye). However, it is observed as a blurred, moving image. The main contributor to the distortion of the stellar image is atmospheric turbulence.2]-[7]. Turbulent layers in the atmosphere cause index of refraction variations that distort the plane wave fronts that ideally should be observed.[4]-[7] A telescope's theoretical angular resolution may be smaller than an arc-sec, but the image resolution will be limited further by atmospheric seeing conditions. Seeing may be quantified: (2.1) theoretically; (2.2) by measurement; (2.3) by combining techniques –

1.1. Theory: modelling with LESNIC

The atmospheric boundary layer is described by a set of differential equations and appropriate boundary conditions. Local unstable air masses (eddies) are either resolved (large eddies) or modelled (small eddies).8]. Assuming a Kolmogorov model of turbulence [9], a profile of turbulence strength as a function of altitude, $C_{\mathrm{N}}{}^2(h)$, may be determined –

$$C_{\mathrm{N}}{}^2(h) = \left(80\times10^{-6}\,\frac{P(h)}{T^2(h)}\right)^2 \quad C_{\mathrm{T}}{}^2(h) \tag{1}$$

where $C_{\mathrm{T}}{}^2(h)$ is the temperature profile of the atmosphere, h the height above the telescope, P is the pressure in hPa and T the absolute temperature in K [10]. The C_T^2 parameter is obtained from the rates of temperature variance dissipation, ε_θ and turbulence kinetic energy dissipation, $\varepsilon^{-1/3}$,

$$C_T^2 = 1.6 \quad \varepsilon_\theta \quad \varepsilon^{-1/3} \tag{2}$$

The LESNIC model will be employed to deliver the profile of turbulence strength as a function of altitude (also referred to as the index of refraction structure parameter or structure constant).

1.2. Preliminary results using LESNIC

The test for the large-eddy simulation technique for determining seeing conditions has used the DATABASE64, which consists of a collection of LESNIC runs for a stably stratified planetary boundary layer (SBL) over a homogeneous aerodynamically rough surface [16].

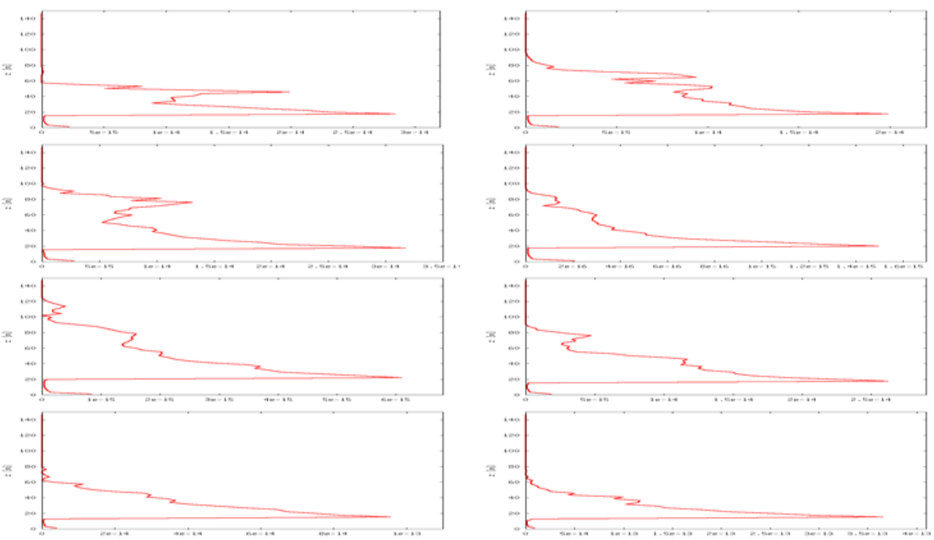

Figure 4. Profiles for $C_N^{\,2}(h)$ obtained with LENIC.

Figure 4 presents eight runs with LESNIC, which cover range of stability conditions in PBL. The quantitative shape of the $C_N^{\,2}(h)$ profiles is quite reasonable.

In Figure 5 the comparison of one of the LESNIC runs with data from [17]. This paper presents 3 1/2 years of site testing data obtained at Dome C, Antarctica, based on measurements obtained with three DIMMs located at three different elevations. Basic statistics of the seeing and the isoplanatic angle are given, as well as the characteristic time.

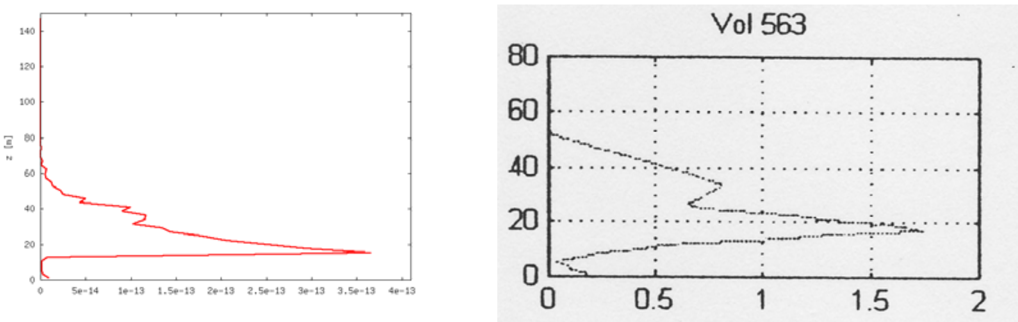

Figure 5. $C_N^{\,2}(h)$ profiles (left panel obtained with LESNIC), right profile from [17] (The horizontal axis is in units of 10^{-13} $m^{-2/3}$).

The figure illustrates LESNIC capacity of reproducing observed features of seeing conditions. The future run with LESNIC will use the representative to Matjiesfontein site initial and boundary conditions as well as topography and roughness features. Therefore, the use of the large-eddy simulation technique will allow conducting relevant numerical simulations for determining the long term seeing conditions at the proposed site as well as the conditions for a particular observation periods.

1.3 Measurement: seeing monitor

By determining the smallest resolvable angle, atmospheric seeing conditions can be measured [7]. The system consists of a telescope, CCD camera and control/processing PC. Seeing varies spatially as well as temporally.[6],[7] Stars at various positions on the night sky will be observed from various on-site locations. Seeing varies at a rate of more than 100 times a second. Numerous short exposure images of a specific source will be captured, evaluated individually, as well as stacked to obtain an average output image, the Point Spread Function (PSF). The PSF is broadened by poor seeing conditions.[4] It will be compared with the theoretical Airy function, which describes the image under ideal conditions (i.e. how the image would appear outside the Earth's atmosphere). A quantitative measure of the seeing will be obtained by fitting a Gaussian intensity distribution to the PSF and determining the Full Width at Half Maximum (FWHM). The FWHM of a star's intensity distribution at the focus of the telescope describes the seeing. It is given by the standard deviation from the Gaussian distribution, σ [11] –

$$\varepsilon_{\mathrm{FWHM}} = \mathrm{FWHM} = 2\sqrt{2\ \ln 2}\ \ \sigma \approx 2.355\ \ \sigma \tag{3}$$

The Fried parameter, r_0,[12],[13] is a statistical parameter to characterise the seeing and is related to the $C_N^{\ 2}$ profile as follows –

$$r_0 = \left(16.7\lambda^{-2}\frac{1}{\cos\gamma}\int_0^{\infty} C_N^{\ 2}(h)\ \mathrm{d}h\right)^{-3/5} \tag{4}$$

where the turbulence strength $C_N^{\ 2}(h)$ varies as a function of height h above the telescope, γ is the zenith angle and λ is the wavelength of observation.[2] A larger Fried parameter indicates better seeing conditions.

Seeing is related to the Fried parameter, r_0, by –

$$\varepsilon_{\mathrm{FWHM}} = 0.98\ \frac{\lambda}{r_0} \tag{5}$$

where λ is the wavelength of observation.[12],[13]

From Equations (3) and (4) above, the relation between seeing and the profile of turbulence strength as a function of altitude, $C_N^{\ 2}(h)$, follows [14]–

$$\varepsilon_{\mathrm{FWHM}} = 0.98\ \frac{\lambda}{r_0} = 5.25\lambda^{-1/5}\left(\int_0^{\infty} C_N^{\ 2}(h)\ \mathrm{d}h\right)^{-3/5} \tag{6}$$

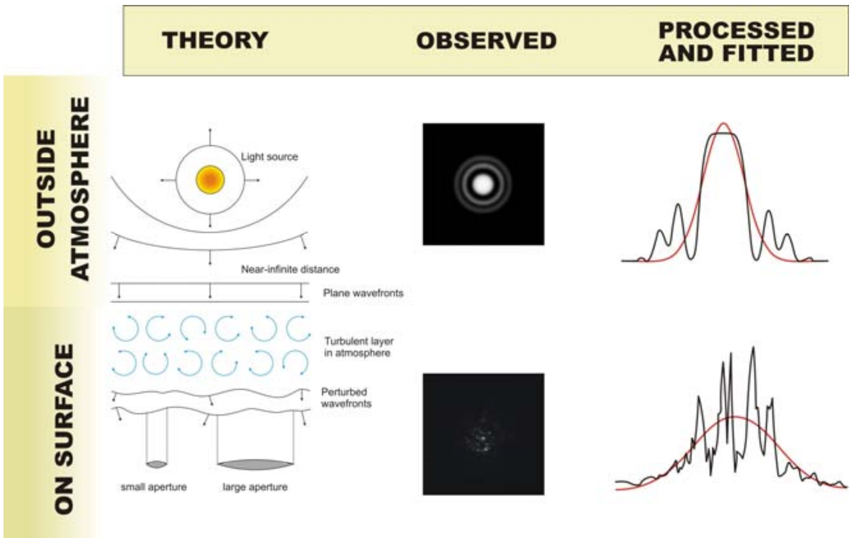

Figure 4. Seeing monitor – technique.

1.2. Combination of techniques and anticipated outcomes

Methods from astronomical seeing and boundary layer meteorology need to be combined to connect optical seeing conditions with atmospheric turbulence.[6] Boundary layer meteorology may be determined by turbulence-resolving numerical modelling with LESNIC[15]. Optical seeing conditions may be determined by implementation of an automated seeing monitor on-site.[2] Seeing monitor data can then be compared with modelled results: (1) to determine whether LESNIC is suitable for modelling seeing conditions; (2) to fine-tune the model to make its seeing quality predictions more accurate. If a good correlation between actual seeing quality and the LESNIC model's predicted results can be found, it would be possible to employ meteorological data together with the LESNIC model to select a suitable observing site as well as to forecast seeing quality at the site.

1.3 Some preliminary results using LENIC

2. Conclusion

Seeing is one of the most important characteristics in determining whether a site is suitable for a space geodetic observatory. Sub arc-sec seeing conditions are required for LLR in particular. It would be possible to determine seeing conditions at the Matjiesfontein site by making use of an automated seeing monitor. The LESNIC model will be fine-tuned, using seeing monitor data. This will be used for seeing predictions in future.

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References

[1] Combrinck WL, Fourie CJS, Croukamp L and Saunders I 2007 Report on preliminary geotechnical and tropospheric site investigation for a proposed space geodetic observatory near Matjiesfontein in the Great Karoo *South African Journal of Geology* **110** 225-234

[2] Roddier F 1981 The effects of atmospheric turbulence in optical astronomy *Progress in Optics* **19** 281-376

[3] Coulman CE 1985 Fundamental and applied aspects of astronomical seeing *Annual Review of Astronomy and Astrophysics* **23** 19-57

[4] Roggeman MC and Welsh B 1996 *Imaging through turbulence* New York: CRC reference

[5] Erasmus DA 2000 Meteorological conditions affecting observing quality on Mauna Kea *Publications of the Astronomical Society of the Pacific* **98** 254-259

[6] Erasmus DA 1988 and 1996 Relating Seeing Quality To Meteorological conditions: Development of Seeing Quality Forecasts and Improvement of Site Selection Procedures http://www.saao.ac.za/~erasmus/overfsee.htm

[7] Erasmus DA 2000 Meteorological conditions and astronomical observing quality ('seeing') at candidate sites for the Southern African Large Telescope *South African Journal of Science* **96** 1-8

[8] Garratt JR 1992 *The atmospheric boundary layer* Cambridge atmospheric and space science series: Cambridge Univeristy Press 224-227

[9] Kolmogorov AN 1941 The local structure of turbulence in incompressible viscous fluid for very large Reynolds' numbers *Comptes rendus (Doklady) de l'Academie des Sciences de l'URSS* **30** 301-305

[10] Tatarski VI 1961 *Wave propagation in a turbulent medium* New York: Dover Publications 79

[11] Wargau WF 1994 Comparing seeing measurements at SAAO/Sutherland, Gamsberg/Namibia and ESO/La Silla *Monthly Notices of the Astronomical Society of Southern Africa* **53** (9 & 10) 88

[12] Fried DL 1965 Statistics of a geometric representation of wavefront distortion *Journal of the Optical Society of America* **56** (10) 1427-1435

[13] Fried DL 1966 Optical resolution through a randomly inhomogeneous medium for very long and very short exposures *Journal of the Optical Society of America* **56** (10) 1372-1379

[14] Vernin J and Muñoz-Tuñón C 1992 Optical seeing at La Palma Observatory, I. General guidelines and preliminary results at the Nordic Optical Telescope *Astronomy & Astrophysics* **257** 811-816

[15] Esau I 2004 Simulation of Ekman Boundary Layers by Large Eddy Model with Dynamic Mixed Subfilter Closure *Environmental Fluid Mechanics* **4** (3) 273

[16] Esau I 2004 Simulation of Ekman Boundary Layers by Large Eddy Model with Dynamic Mixed Subfilter Closure. *Environmental Fluid Mechanics* **4** (3) 273

[17] Aristidi E, Fossat E, Agabi A, Mékarnia D, Jeanneaux F, Bondoux E, Challita Z, Ziad A, Vernin J and Trinquet H ,2009,Dome C site testing: surface layer, free atmosphere seeing, and isoplanatic angle statistics. *Astronomy & Astrophysics* **499** 955