Baseline design of the KunLun Turbulence Profiler instrument (Postprint)

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Date: 2024-07-31T00:00:00+00:00

Abstract

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Full Text

Preamble

Astronomical Techniques and Instruments, Vol. 1, July 2024, 218–226

Article

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Baseline Design of the KunLun Turbulence Profiler Instrument

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Received: March 25, 2024; Accepted: April 18, 2024; Published Online: May 6, 2024
https://doi.org/10.61977/ati2024028

Citation: Guo, X. H., Hu, Y., Li, J., et al. 2024. Baseline design of the KunLun Turbulence Profiler instrument. *Astronomical Techniques and Instruments*, 1(4): 218–226. https://doi.org/10.61977/ati2024028.

Abstract

Adaptive optics systems are the most powerful tools to counteract image blurring caused by atmospheric turbulence, allowing ground-based telescopes to capture high-resolution images. A critical parameter influencing adaptive optics system performance is the atmospheric refractive index structure constant, C_n^2, which characterizes the intensity of atmospheric optical turbulence as a function of altitude. Given its simplicity, the lunar scintillometer is the preferred method for detecting atmospheric turbulence in challenging environments like Dome A in Antarctica, where sites are still in developmental stages and local environmental conditions are extremely harsh. However, optimizing the performance of such instruments requires carefully determining the baseline configuration of photon sensors according to each site's specific optical turbulence profile characteristics. This study uses a Monte Carlo method to identify the optimal configuration for the KunLun Turbulence Profiler (KLTP), an instrument comparable to the lunar scintillometer, developed for use at Dome A. Simulations conducted using the obtained optimal baseline configuration recovered three different model optical turbulence profiles, demonstrating the effectiveness of our method in obtaining an optimal baseline configuration. Our approach can be easily applied to baseline design for similar turbulence profilers at other sites.

Keywords: KunLun Turbulence Profiler; Monte Carlo; Simulation; Turbulence profile

1. Introduction

Ground-based telescopes can easily produce blurred images of their targets due to astronomical "seeing," caused by the passage of light through the turbulent refractive atmosphere before reaching Earth's surface [?]. In 1953, Babcock [?] proposed a groundbreaking solution using light from a reference star to detect wavefront phase and correct phase fluctuations with a deformable mirror. This revolutionary technique is known as adaptive optics (AO), effectively mitigating the blurring effects on astronomical objects and allowing telescopes to approach their theoretical diffraction limit [?]. AO systems have become indispensable in contemporary astronomical instrumentation, especially for large telescopes [?]. The construction of an AO system involves numerous parameters, with one of the most crucial being the atmospheric refractive structure constant, C_n^2. This parameter represents the intensity of atmospheric optical turbulence as a function of height [?]. Several techniques have been developed for measuring C_n^2, which can be broadly categorized into optical and non-optical methods.

Optical methods for measuring C_n^2 include Multi-Aperture Scintillation Sensor (MASS), SCIntillation Detection And Ranging (SCIDAR), Slope Detection And Ranging (SLODAR), Shadow Band Array (SHABAR), and Lunar Scintillometer (LuSci). The MASS method uses optics with four concentric apertures to sample the flux of a bright star, which acts as a spatial filter. The optical turbulence profile (OTP) is then derived from the scintillation indices—the variance of light intensity fluctuations—from measurements of different apertures [?]. MASS needs a small telescope that can detect turbulence up to an altitude of 16 km at low resolution [?]. However, it is insensitive to turbulence below 500 m. The SCIDAR method computes the covariance (autocorrelation and cross-correlation processing) using short-exposure-time images of the scintillation pattern by a double star [?, ?] and uses it to deduce C_n^2. SCIDAR needs a 1 m-class telescope that can detect turbulence up to an altitude of 20 km with a medium resolution of 300 m for the OTP. The vertical resolution of SCIDAR depends on the angular separation of the target binary stars and the zenith angle [?, ?]. SLODAR uses the measurement of wavefront slopes of two guide stars using Shack-Hartmann wavefront sensors. The OTP is then computed based on the cross-correlation and autocorrelation of these slopes [?, ?]. Like SCIDAR, SLODAR also needs a 1 m-class telescope.

Another optical method is to observe extended sources, such as the Sun and the Moon. Beckers [?] proposed SHABAR, which uses solar scintillation to profile turbulence in the ground layer. SHABAR comprises six photon sensors arranged in a linear, non-redundant configuration [?, ?]. The covariances of sunlight intensity fluctuations among individual sensors are measured and used to reconstruct the OTP to within 500 m [?]. LuSci, a SHABAR variant, was introduced to measure moonlight intensity fluctuations to deduce the nighttime profile [?], using an equatorial mount to track the Moon [?, ?, ?]. To account for low temperatures and challenging environments in the Arctic, Paul [?] developed the Arctic Turbulence Profiler (ATP) for measuring the OTP at Pearl Station. Instead of being mounted onto a telescope, ATP comprises 48 sensors arranged in six rings along a vertical axis at different heights. The Moon sequentially illuminates one sensor in each ring as the Earth rotates. A computer then selects the appropriate sensor for data collection, enabling the Moon to be tracked without any physical motion of the instrument [?]. In addition to these optical methods, a new technique involves capturing a sequence of short-exposure images of a star field using a small telescope. This technique uses the differential motion between all pairs of star images to calculate the structure functions of longitudinal and transverse wavefront tilt across various angular separations. This method can estimate the OTP in the lower atmosphere, determine the total and free-atmosphere seeing, and provide information about the outer scale [?].

Non-optical methods for atmospheric turbulence measurement include ballooning and SNODAR (Surface layer NOn-Doppler Acoustic Radar). Ballooning involves deploying micro-thermal sensors attached to weather balloons, enabling the measurement of thermal fluctuations. This method facilitates the deduction of the vertical distribution of C_n^2 [?]. In contrast, SNODAR uses ultrasound scattering through turbulent air to infer atmospheric turbulence conditions [?].

The characteristics of all these methods are summarized in Table 1 .

Dome A is the highest point in the inland Antarctic region, boasting exceptionally favorable astronomical observation conditions in the optical wavelength range [?, ?]. Bonner [?] derived a median atmospheric boundary layer thickness of only 13.9 m at Dome A using data from SNODAR measurements. However, SNODAR could only retrieve a relative C_n^2 profile because of the lack of calibration data [?]. Analysis of data from the KunLun Automated Weather Station (KLAWS) and its second-generation version KLAWS-2G revealed the presence of a strong temperature inversion layer with moderate wind speed at the surface of Dome A, confirming the atmospheric stability and thin boundary layer at Dome A [?, ?].

Recently, free atmospheric seeing of 0.31” can be obtained for 31% of the time at an altitude of only 8 m [?]. Additionally, Chinese Small Telescope Array (CSTAR) data analysis indicates a sky brightness of 20.5 mag/square arcsecond in the i-band at Dome A on moonless nights [?]. Analysis of data from the Kunlun Cloud and Aurora Monitor (KLCAM) in 2017 revealed that Dome A experiences a high percentage of clear nights, reaching as high as 83%, making it superior to other observatory sites [?]. To date, however, there is no known ground-based astronomical C_n^2 profile data for this site because of the extremely low-temperature environment [?].

As shown in Table 1, the LuSci, not necessitating any moving parts [?, ?], exhibits a higher probability of sustained and continuous operation at Dome A, especially when coupled with appropriate thermal design measures. Moreover, the atmospheric turbulence is predominantly concentrated in the boundary layer, particularly at Dome A, where the boundary layer spans only a few tens of meters, allowing for a free atmospheric seeing of 0.31". These findings imply that the turbulence in the ground layer is concentrated within a range of several tens of meters. The LuSci stands out as an ideal instrument for precisely measuring turbulence within this altitude range, establishing its unequivocal suitability as the primary turbulence measurement tool which uses the lunar scintillation method to develop the KLTP for the measurement of the C_n^2 profile at Dome A.

The KLTP is structured similarly to the ATP, comprising 64 sensors arranged into 8 sensor rings, totaling 28 baselines. Each pair of sensors forms a baseline, and the distance of each baseline determines the detected turbulence altitude. Therefore, the length and the number of the baseline configuration directly influences the detection altitude and resolution of the instrument. More importantly, this determines how capable it is of recovering the C_n^2 profile. Because turbulence characteristics vary across different sites, it is crucial to tailor the instrument baseline design to the specific OTP of each observation site.

Deriving the baseline configuration directly through analytical formulas is difficult. Therefore, we employ a Monte Carlo method to determine the optimal baseline configuration for the KLTP. We randomly generate a sample pool that contains 10 million baseline candidates and use three distinct methods to select the most optimal baseline. Finally, we conduct simulations employing various configurations to reconstruct diverse model OTPs. The results confirm that our method can effectively find optimized baseline configurations.

This paper is organized as follows: in Section 2, we briefly introduce the principles of KLTP and describe our baseline design method. Then, in Section 3, we validate the baseline design using numerical simulations. In Section 4, we summarize, discuss the effects of redundancy and noise, and conclude.

2.1. Principles of the KLTP and its Baseline

The principle of the KLTP is straightforward: two sensors receive light signals from an extended source, and the light paths begin to overlap at a specific height proportional to the separation between the detectors, resulting in non-zero intensity covariance. Such non-zero covariance contains information about optical turbulence below the height at which it occurs, so by adopting several sensors measuring the scintillation of the extended source, the C_n^2 profile can be recovered. As illustrated in Fig. 1 [Figure 1: see original paper], the baseline b_0 is the distance between the two sensors, and the relation between the detection altitude h and the baseline can be approximately expressed as

$$b_0 = \frac{h \sin A}{1 - \cos A} = \frac{2h}{\sin 2A}, \tag{1}$$

where A is the elevation angle of the Moon, and α is the angular diameter of the Moon. Using an array of sensors offering numerous independent baselines, it becomes possible to determine the C_n^2 profile of the optical turbulence [**?**].

The parameters in Equation (1) that determine the detection altitude of a baseline are chosen as follows. Because the atmospheric boundary layer at Dome A is concentrated below several tens of meters in altitude [**?**], we set the detection altitude range of the KLTP between 5 m and 50 m, effectively covering the boundary layer turbulence at Dome A. To ensure the reliability of the data from the KLTP, we impose restrictions on the elevation of the Moon above 20° and the Sun below −13°. Fig. 2 [Figure 2: see original paper] shows the Moon elevation and phase and the Sun elevation as functions of the time in 2024. When the Dome A site enters into astronomical nighttime [**?**], there is much time when the moon phase is close to full, and the elevation of the Moon is approximately 30°. Therefore, we fixed A at 30° and α at 0.5° when calculating the baseline design.

2.2. Baseline Design Method

Because the detection range for the KLTP is from 5 m to 50 m, the shortest and longest baselines are 10 cm and 100.7 cm, respectively. We generate six random numbers uniformly distributed from 0 to 100.7 cm, and these six random numbers give the positions of the sensors. For each configuration, we have 28 baselines. As such, we obtain a single baseline configuration, and repeat this procedure until we get a sample pool of 10 million configurations.

Then, we exclude those configurations with a minimum baseline length less than the shortest baseline or longer than 1.05 times the shortest baseline from the sample pool. Next, we select the baseline configuration with the most uniform detection altitudes in the logarithmic space. The reason behind this is that the variation in atmospheric turbulence intensity with altitude closely resembles the decay of an exponential function [**?**]. By uniformly sampling in the logarithmic space, we can efficiently reconstruct the OTP with minimal cost.

Three filtering methods are employed to identify the most uniformly distributed baseline configuration in the sample pool. The first method is the mean inequality (MI) approach, in which the merit of uniformity for each baseline configuration is determined as the sum of the inverse of the differences between adjacent baselines in the logarithmic space, as defined by

$$M = \sum_i \frac{1}{x_i}, \tag{2}$$

where x_i is the difference in length between two adjacent baselines in the logarithmic space, and x is the set of all such differences.

The second is the variance method, with the merit of being the inverse of the variance, given by

$$M = \frac{1}{\mathrm{var}(x)}. \tag{3}$$

The third is the mean deviation (MD) method, with the merit of being the inverse of the sum of the absolute differences where the mean value of x is subtracted from each x_i, given by

$$M = \frac{1}{\sum_j |x_i - \bar{x}_j|}. \tag{4}$$

Fig. 3 [Figure 3: see original paper] illustrates the best, median, and worst baseline configurations resulting from the three methods; the best configuration is more uniform than the median and the worst cases. Specifically, the worst configuration exhibits obvious gaps and closely clustered baselines. In contrast, the best configuration showcases greater uniformity, featuring smaller gaps and the absence of baseline clustering compared with the other cases.

Finally, we select the best baseline configuration among the best results from the three methods. As illustrated in Fig. 3D, the mean deviation and the mean inequality methods yield the same results, showing a gap at -0.75 in the logarithmic space. In contrast, the best baseline configuration obtained from the variance method exhibits no significant gap. It has more baselines in the first half of the logarithm space than the other two methods. Therefore, we choose the best case from the variance method as our optimal baseline configuration in this experiment. Because the random seed might affect the results of our Monte Carlo method, we also generate another 49 sample pools using different seeds. Across those 50 sample pools, the variance method yields approximately 38% optimal baseline configurations, while the mean inequality generates roughly 20% and the mean deviation generates approximately 52%. Therefore, when designing a LuSci-like turbulence profiler, we must compare the baselines of the above three methods and select the baseline that is most uniform in the logarithmic space.

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3. Simulation and Validation

We perform numerical simulations to confirm the applicability of the above baseline selection for retrieving the C_n^2 profile at Dome A. The theoretical fundamentals of a LuSci-like turbulence profiler are presented in the references [**?**, **?**, **?**, **?**]. The sensors of the KLTP frequently record the light intensity of the Moon. Then, the intensity covariance $C_I(r_i)$ for each sensor pair is easily calculated. The relation between $C_I(r_i)$ and the C_n^2 profile can be expressed as [?]

$$C_I(r_i) = \int_0^{10} C_n^2(z; \cos\theta) W(r_i; z)\, dz, \tag{5}$$

where $W(r_i; z)$ is the response function and z represents the height above the ground [?]. According to Equation (5), the C_n^2 profile can be extracted from these covariances by many methods, for instance, maximum entropy (ME) analysis [?].

To perform our simulations, we generate a simulated C_n^2 profile using Equation (5) for given $C_I(r_i)$ and $W(r_i; z)$. The response function $W(r_i; z)$ can be written as an integral over spatial frequency κ, weighted by filter functions F_L, F_K, F_Ω, and F_D:

$$W(r_i; z) = \left(-\frac{8}{3}\right) \sin\left(\frac{\pi}{3}\right) \frac{z^2}{2\pi} \int d^2\kappa\, \kappa^{-1/3} e^{i\kappa\cdot r_i} F_L(\kappa) F_K(\kappa; z) F_\Omega(\kappa) F_D(\kappa). \tag{6}$$

These factors affect the modification of the frequency spectrum: the outer scale of turbulence, diffraction, the finite angular size and shape of the Moon, and the finite size and shape of the detectors [?]. Our simulations are conducted under full moon conditions. The outer scale is set to 20 m, because near the ground, the outer scale is approximately equal to the height above the ground [?]. The seeing value is set to 0.8" for all simulations, as the median seeing value of 8 m at Dome A [?]. Because sensor noise is unavoidable, we incorporate Gaussian noise into each simulated $C_I(r_i)$. Finally, we adopt the ME method to retrieve the C_n^2 profile and compare it with the input models.

The first model we use is the step model, which assumes atmospheric turbulence to consist of two components: the free atmosphere, where turbulence is weak, and the boundary layer, characterized by strong turbulence. The results of recovering the step model OTP using the best, median, and worst baseline configurations are shown in Fig. 4 [Figure 4: see original paper], in which the solid black line represents the original step model and the colored lines represent recovery results with varying noise levels. The root mean square error (RMSE) between the original model C_n^2 profile and the simulation results is labeled in Fig. 4 and the calculation scope of the RMSE is $\log z < 1.75$. Without covariance noise, the best baseline is more accurate than the others in retrieving the OTP. The median case cannot recover the model well, and the worst case produces noise in the retrieval. As the covariance noise increases, the RMSE also increases. Neither case can recover the OTP when the noise is greater than 0.02.

The second model is the bimodally distributed C_n^2 profile. This model is more likely to simulate the near-surface OTP at Dome A, as such a structure has been observed at Dome C [**?**]. Moreover, it allows for the observation of substructures within OTPs. The results are shown in Fig. 5 [Figure 5: see original paper]. When the Gaussian noise is absent, the best and median cases can recover the OTP with an RMSE of less than 0.03. Conversely, the result of the worst case cannot be recovered with an RMSE greater than 0.05. As the noise increases, the RMSE also increases. However, the best case always has a smaller RMSE value than the median and worst cases. When the noise is larger than 0.05, none of the three cases can recover the OTP with an RMSE larger than 0.05.

We also use the ATP baseline configuration [**?**] to simulate the bimodal model for comparison. As shown in Fig. 5D, even without noise present, the ATP baseline configuration cannot recover the model profile well, especially in the region of $\log z < 1.5$. Therefore, the baseline configuration of LuSci-like instruments should be redesigned according to individual site characteristics.

The third model is the Hufnagel/Andrews/Phillips (HAP) model, which is an improved version of the mainstream atmospheric turbulence Hufnagel-Valley (H-V) model [**?**]. The HAP model modifies parameters near the ground to make the near-surface range of the C_n^2 profile a closer match to true measured values [**?**]. Our simulation results show that when the noise level is below 0.01, the RSMEs with the best baseline configuration are less than 0.05 for the step and the bimodal models, indicating satisfactory retrieved results. Here, the median and worst configurations cannot recover the OTP well, as illustrated by Fig. 4 and Fig. 5. As the noise increases, we still cannot retrieve results with an RMSE less than 0.05, even with the best configuration. We conclude that we must constrain the covariance error to within 0.01 to obtain a reliable measurement for the KLTP.

Fig. 6 [Figure 6: see original paper] shows the simulation results of the HAP model. All cases can recover the OTP well, even when the noise is set to 0.1, possibly because the HAP model is analytic and smooth.

4. Discussion and Conclusions

A LuSci-like turbulence profiler is an excellent way to measure the C_n^2 profile at harsh and unattended sites. However, the baseline configuration of such an instrument should be carefully designed to optimize its capabilities. Here, we apply a Monte Carlo method to search for the best baseline configuration for the KLTP, which can sample the OTP most uniformly in the logarithmic scale. We use three filtering methods to measure the uniformity in the baseline configuration, and we must adopt all these methods to select the best configuration. Finally, we perform simulations to verify the baseline configuration, and our results confirm that the Monte Carlo method is an effective way to obtain an optimal baseline configuration. Our method can also be applied to LuSci-like turbulence profilers at other sites. However, our simulations show that the sensor noise has a profound impact on the performance of the KLTP and must be minimized.

4.1. Impact of Sensor Noise

Noise has a significant influence on the retrieval of OTPs, as evidenced by the simulation results in Section 3. When the input noise is larger than 0.02, even with the best baseline, we cannot recover the OTP well (i.e., when RMSE is greater than 0.05). Therefore, it is critical to reduce the noise as much as possible. Because the photon sensors are one source of covariance error, the KLTP needs high-precision sensors, and their read-out circuits must be carefully designed. The other source of covariance error is photon noise, which is proportional to the root square of the intensity of the moonlight. Consequently, when operating at Dome A, the OTP we recovered using the KLTP will be more reliable when the elevation of the Moon is higher and the phase of the Moon is larger. We plan to operate the KLTP at Dome A only when the Moon's elevation is higher than 20°. However, the total observation time of the KLTP will be reduced to 577 hours by such constraints, which means we only have 22% time with OTP measurements during the polar night [**?**], when the Sun is below $-13°$. Fortunately, we have KLAWS-2G to measure multi-layer meteorological parameters up to an altitude of 14 m [**?**, **?**] and KL-DIMM at 8 m to monitor the atmospheric seeing at Dome A [**?**]. Because the optical turbulence is related to the meteorological parameter, it might be possible to estimate the OTP only from KLAWS-2G and KL-DIMM data. Therefore, the simultaneous observation of these three instruments is vital for continuously monitoring the OTP at Dome A during astronomical twilight [**?**]. Additionally, the day-to-day temperature fluctuation can be as significant as 30 °C at Dome A, and the air is super-saturated, causing the window of the photon sensor to be vulnerable to frost. Consequently, defrosting should also be thoroughly considered.

4.2. Redundancy

The KLTP has eight sensors in each column, whereas the ATP has only six. Apart from aiming to capture details of atmospheric turbulence within the 5–50 m range, the other reason is to prevent the degradation of data quality from potential sensor damage under extreme conditions. Fig. 7 [Figure 7: see original paper] illustrates the best baseline configuration obtained above and a configuration that removes the fourth sensor from the best. Here, the baselines decreased from 28 to 21, and the corresponding altitudes lost were 0.7, 0.78, 1.08, 1.11, 1.3, 1.34, and 1.48 on the logarithmic scale.

The numerical simulation results of such a sensor-lost configuration are shown in Fig. 8 [Figure 8: see original paper]. When the input noise is 0, the RMSE increases by 135% compared with the best baseline configuration result. Although the RMSE is still below 0.05, the OTP at the lower height cannot be recovered well in this case. However, the OTP at increased height can be recovered precisely. As the input covariance error increases, the RMSE also increases dramatically. Even if the error is 0.01, the RMSE is much larger than 0.05, but the lost baselines dominate the RMSE. Therefore, we conclude that when a sensor on the KLTP gets damaged, recovering the rest of the OTP is still possible but requires more stringent noise control. This work lays the foundation for the operation of KLTP in Dome A and also provides a solution for the baseline design of similar instruments.

Acknowledgements

The authors thank Dr. Paul Hickson for his original code for baseline design and numerical simulation, and we also appreciate Dr. Zhaohui Shang, Dr. Bin Ma, and Dr. Feng Lu for their helpful comments. This work was financially supported by the National Natural Science Foundation of China (12373092, 11733007, 11873010, 12133010, 12273027), the Nebula Talents Program of the National Astronomical Observatories, Sichuan Youth Science and Technology Innovation Research Team (21CXTD0038), and the Innovation Team Funds of China West Normal University (KCXTD2022-6).

Author Contributions

Xiaohui Guo designed and implemented the study and wrote the paper. Yi Hu, Jing Li, Xu Yang, and Zhengzhou Yan performed the statistical analysis and revised the paper. All authors read and approved the final manuscript.

Declaration of Interests

The authors declare no competing interests.

References

1. Davies, R., Kasper, M. 2012. Adaptive optics for astronomy. *Annual Review of Astronomy and Astrophysics*, 50: 305—351.
2. Babcock, H. W. 1953. The possibility of compensating astronomical seeing. *Publications of the Astronomical Society of the Pacific*, 65(386): 229—236.
3. Hardy, J. W. 1998. *Adaptive Optics for Astronomical Telescopes*. Oxford: Oxford University Press.
4. Hickson, P. 2014. Atmospheric and adaptive optics. *The Astronomy and Astrophysics Review*, 22: 1—38.

5. Tokovinin, V. 2007. Accurate seeing measurements with MASS and DIMM. *Monthly Notices of the Royal Astronomical Society*, 381(3): 1179−1189.
6. Kornilov, V., Tokovinin, A., Shatsky, N., et al. 2003. Restoration of turbulence profile from scintillation indices. *Monthly Notices of the Royal Astronomical Society*, 343(3): 891−899.
7. Avila, R., Vernin, J., Sánchez, L. J. 2001. Atmospheric turbulence and wind profiles monitoring with generalized scidar. *Astronomy and Astrophysics*, 369(1): 364−372.
8. Gagné, P., Gu, W. 2002. SLODAR: Measuring optical turbulence altitude with a Shack–Hartmann wavefront sensor. *Monthly Notices of the Royal Astronomical Society*, 337(1): 103−108.
9. Wilson, R. W., Butterley, T., Sarazin, M. 2009. The Durham/ESO SLODAR optical turbulence profiler. *Monthly Notices of the Royal Astronomical Society*, 399(4): 2129−2138.
10. Beckers, J. M. 2001. A seeing monitor for solar and other extended object observations. *Experimental Astronomy*, 12: 1−20.
11. Tokovinin, A. 2004. Turbulence profiles from the scintillation of stars, planets and moon. In *Proceedings of Workshop on Astronomical Site Evaluation*.
12. Hickson, P., Lanzetta, K. 2004. Measuring atmospheric turbulence with a lunar scintillometer array. *Publications of the Astronomical Society of the Pacific*, 116(826): 1143.
13. Hickson, P., et al. 2013. Astronomical seeing and ground-layer turbulence in the Canadian High Arctic. *Monthly Notices of the Royal Astronomical Society*, 433(1): 307−312.
14. Hickson, P., Feng, L., Hellemeier, J. A., et al. 2020. Optical turbulence at Ali, China—results from the first year of lunar scintillometer observations. *Monthly Notices of the Royal Astronomical Society*, 494(4): 5992−6000.
15. Rajagopal, J., Tokovinin, A., Bustos, E., et al. 2008. LuSci: a lunar scintillometer to study ground layer turbulence. In *Proceedings of SPIE, Optical and Infrared Interferometry*, 7013: 70131P.
16. Lombardi, G., Sarazin, M., Char, F., et al. 2013. Surface layer turbulence profiling with the SL-SLODAR and LuSci at ESO Paranal Observatory. In *Proceedings of XIV Latin American Regional IAU Meeting*.
17. Hickson, P., Ma, B., Shang, Z. H., et al. 2019. Multistar turbulence monitor: a new technique to measure optical turbulence profiles. *Monthly Notices of the Royal Astronomical Society*, 485(2): 2532−2545.
18. Agabi, A., Aristidi, E., Azouit, M., et al. 2006. First whole atmosphere nighttime seeing measurements at Dome C, Antarctica. *Publications of the Astronomical Society of the Pacific*, 118(840): 344.
19. Bonner, C. S., Ashley, M. C. B., Lawrence, J. S., et al. 2008. Snodar: a new instrument to measure the height of the boundary layer on the Antarctic plateau. In *Ground-based and Airborne Instrumentation for Astronomy II*, SPIE, 7014: 2262−2268.
20. Shang, Z. H. 2020. Astronomy from Dome A in Antarctica. *Research in*

Astronomy and Astrophysics, 20(10): 168.

21. Bonner, C. S., Ashley, M. C. B., Cui, X., et al. 2010. Thickness of the atmospheric boundary layer above Dome A, Antarctica. *Publications of the Astronomical Society of the Pacific*, 122(895): 1122.
22. Hu, Y., Shang, Z. H., Ashley, M. C. B., et al. 2014. Meteorological data for the astronomical site at Dome A, Antarctica, during 2009. *Publications of the Astronomical Society of the Pacific*, 126(943): 868.
23. Hu, Y., Hu, K. L., Shang, Z. H., et al. 2018. Meteorological data from KLAWS-2G for an astronomical site survey of Dome A, Antarctica. *Publications of the Astronomical Society of the Pacific*, 131(995): 015001.
24. Ma, B., Shang, Z. H., Hu, Y., et al. 2020. Night-time measurements of astronomical seeing at Dome A in Antarctica. *Nature*, 583(7818): 771−774.
25. Zou, H., Zhou, X., Jiang, Z. J., et al. 2010. Sky brightness and transparency in the i-band at Dome A, Antarctica. *The Astronomical Journal*, 140(2): 602.
26. Yang, X., Shang, Z. H., Hu, K. L., et al. 2021. Cloud cover and aurora contamination at dome A in 2017 from KLCAM. *Monthly Notices of the Royal Astronomical Society*, 501(3): 3614−3620.
27. Aristidi, E., Agabi, A., Fossat, E., et al. 2012. Dome C site testing: long term statistics of integrated optical turbulence parameters at ground level. *Proceedings of the International Astronomical Union*, 8(S288): 300−301.
28. Masciadri, E., Stoesz, J., Hagelin, S., et al. 2010. Mt. Graham: Optical turbulence vertical distribution at standard and high vertical resolution. arXiv:1011.5583.
29. Trinquet, H., Agabi, A., Vernin, J., et al. 2008. Nighttime optical turbulence vertical structure above Dome C in Antarctica. *Publications of the Astronomical Society of the Pacific*, 120(864): 203.
30. Andrews, L. C. 2019. *Field Guide to Atmospheric Optics.* California: SPIE.
31. Hickson, P., Pfrommer, T., Crotts, A. P. 2010. Optical turbulence profiles at CTIO from a 12-element lunar scintillometer. *Optical Turbulence*, 26−33.
32. Tokovinin, A., Bustos, E., Berdja, A. 2010. Near-ground turbulence profiles from lunar scintillometer. *Monthly Notices of the Royal Astronomical Society*, 404(3): 1186−1196.
33. Tatarskii, V. I. 1961. *Wave Propagation in a Turbulent Medium.* New York: McGraw-Hill.
34. Aristidi, E., Vernin, J., Fossat, E., et al. 2015. Monitoring the optical turbulence in the surface layer at Dome C, Antarctica, with sonic anemometers. *Monthly Notices of the Royal Astronomical Society*, 454(4): 4304−4315.
35. Andrews, L. C., Phillips, R. L., Wayne, D., et al. 2009. Near-ground vertical profile of refractive-index fluctuations. In *Proceedings of SPIE*, 7324: 732402.

Note: Figure translations are in progress. See original paper for figures.