Advances in Daytime Atmospheric Optical Turbulence Profiling Techniques: Postprint

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Date: 2023-06-07T00:00:00+00:00

Abstract

The atmosphere degrades the imaging quality of telescopes. To mitigate the atmospheric effects on telescopes, it is necessary to select high-quality sites and install adaptive optics systems. Due to solar radiation influence, daytime atmospheric turbulence is often more intense than at night. Currently, numerous solar telescopes both domestically and internationally have been equipped with adaptive optics systems. Traditional adaptive optics systems have drawbacks such as a small field of view; while new wide-field adaptive optics systems can resolve these problems, precise detection of atmospheric turbulence profiles is a prerequisite and key for them. At the same time, high-resolution astronomical imaging techniques based on turbulence imaging theory also require more detailed detection of turbulence. Therefore, daytime atmospheric turbulence profiling techniques are of significant value to astronomical observations. First, the parameters related to atmospheric turbulence are introduced; subsequently, emphasis is placed on daytime atmospheric turbulence profiling techniques including sodar, SHABAR, MOSP, SDIMM+, and A-MASP, summarizing the principles, advantages, and disadvantages of each measurement technique.

Full Text

Preamble

Progress in Astronomy, Vol. 40, No. 3
September 2022
doi: 10.3969/j.issn.1000-8349.2022.03.03

Development Overview of Daytime Atmospheric Optical Turbulence Profile Detection Technology

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Abstract

Atmospheric turbulence degrades telescope imaging quality. To mitigate atmospheric effects, telescopes require both high-quality site selection and adaptive optics systems. Due to solar radiation, daytime atmospheric turbulence is typically more intense than at night. Numerous solar telescopes worldwide have now installed adaptive optics systems. However, conventional adaptive optics suffer from a small field of view, while new wide-field adaptive optics systems can address these limitations—but only with precise atmospheric turbulence profile detection as their prerequisite. Meanwhile, high-resolution astronomical imaging techniques based on turbulence theory also require detailed turbulence characterization. Therefore, daytime atmospheric turbulence profile detection technology holds significant value for astronomical observations. This paper first introduces relevant atmospheric turbulence parameters, then focuses on daytime profiling techniques including SNODAR, SHABAR, MOSP, SDIMM+, and A-MASP, summarizing their principles, advantages, and disadvantages.

Keywords: turbulence profile; site testing; seeing
Classification Code: P427.1
Document Code: A

1 Introduction

Imaging quality is crucial for astronomical observations. A telescope' s imaging performance depends not only on its own capabilities but also critically on its location. The familiar twinkling of stars on clear nights—known as stellar scintillation—represents the most common manifestation of turbulence. Newton conducted detailed analyses of this phenomenon and correctly inferred that stellar scintillation originates from atmospheric jitter, an effect that cannot be eliminated even with large-aperture, long-focal-length telescopes.

When starlight passes through the atmosphere, turbulence degrades imaging quality through four primary effects: image motion, image distortion, image blurring, and intensity scintillation [1]. As technology advances, atmospheric turbulence has become the dominant limitation on observations. Consequently, atmospheric characterization is essential to reduce these constraints. In the absence of turbulence, a telescope would focus starlight to a perfect point; in reality, turbulence produces a speckled image. Figure 1 [Figure 1: see original paper] illustrates the impact of varying turbulence levels on a 25.4 cm telescope, with seeing classifications from V to I corresponding to <0.4 , 0.4 -0.9 , 1.0 -2.0 , 3.0 -4.0 , and >4.0 , respectively.

Once a telescope is installed at a chosen astronomical site, its position and altitude become fixed. To reduce turbulence effects thereafter, adaptive optics systems must be installed. Table 1 lists existing solar adaptive optics systems worldwide, showing that large solar telescopes have either deployed or plan to deploy such systems. Conventional adaptive optics suffer from a limited field of view. On one hand, they require sufficiently bright guide stars within the isoplanatic patch to provide wavefront sensor information. On the other hand, for extended targets, correction works well near the detection field but degrades for distant regions because high-altitude turbulence affects different lines of sight differently, making it impossible for a single deformable mirror to fully correct phase errors from all sightlines. New wide-field adaptive optics systems, such as Multi-Conjugate Adaptive Optics (MCAO) [4] and Ground Layer Adaptive Optics (GLAO) [5] shown in Figure 2 [Figure 2: see original paper], can solve these problems.

MCAO employs multiple guide stars along different sightlines for multi-directional wavefront sensing, simultaneously measuring accumulated wavefront aberrations as light passes through the atmosphere. Atmospheric tomography then reconstructs the data to obtain wavefront errors from turbulence at different altitudes. Multiple deformable mirrors, positioned conjugate to these turbulent layers, provide layered correction, enabling high-resolution imaging over a wide field [6]. However, selecting the most influential turbulent layers and determining their intensity are prerequisites and keys to implementing these new adaptive optics techniques.

Furthermore, during site selection, precise measurement of both integrated atmospheric turbulence and turbulence profiles is necessary to provide design parameters for future adaptive optics systems. This is also crucial for high-resolution techniques like speckle imaging [7] and lucky imaging [8] that rely on turbulence as their theoretical foundation. During daytime, solar radiation makes atmospheric turbulence more intense than at night [9], posing greater challenges for solar adaptive optics and making high-resolution turbulence profiling increasingly necessary. However, daytime requirements have historically been smaller than nighttime needs, resulting in slower development of daytime turbulence profiling technology.

2 Atmospheric Turbulence Parameters

The atmosphere consists of two components: a discrete turbid medium of particles and a “continuous” turbulent medium of thermally moving molecules. The former primarily causes scattering (e.g., blue sky, solar halos), while the latter creates refractive index variations that alter starlight’ s phase and amplitude, destroying coherence and degrading imaging quality [10]. Key turbulence parameters [11] include: refractive index structure constant C_N^2, atmospheric coherence length r_0 and seeing, coherence time τ_0, isoplanatic angle θ_0, inner scale l_0, outer scale L_0, and scintillation index σ^2.

2.1 Atmospheric Refractive Index Structure Constant C_N^2

The atmospheric refractive index structure function represents the expected value of refractive index differences between two points in a homogeneous, isotropic random field. The structure constant C_N^2 describes how refractive index fluctuation intensity varies with altitude, characterizing optical turbulence strength at a point. From the Cauchy formula, air refractive index n can be expressed as a function of atmospheric parameters:

$$n-1=\frac{77.6\times10^{-6}(1+7.52\times10^{-3}\lambda^{-2})P}{T}+\frac{4810e}{T^2}$$

where T is temperature (K), λ is wavelength, P is atmospheric pressure, and e is water vapor pressure. Since water vapor fluctuations are small, the last term is often neglected. The temperature derivative is:

$$\frac{\partial(n-1)}{\partial T}=-\frac{79\times10^{-6}P}{T^2}$$

The coefficient 79×10^{-6} K/hPa applies at 500 nm, varying from 82.9×10^{-6} to 77.5×10^{-6} K/hPa for wavelengths of 300-1000 nm [13]. Thus, C_N depends on temperature and pressure, with pressure related to altitude. As shown in Figure 3 [Figure 3: see original paper], C_N^2 decreases rapidly with altitude because atmospheric pressure drops exponentially from 1×10^5 Pa at sea level to 1×10^3 Pa at 30 km. A secondary maximum occurs at the 10 km tropopause due to frequent wind shear. Turbulence is classified as weak ($< 6.4\times10^{-17}$ m$^{-2/3}$), moderate (2.5×10^{-13}-6.4×10^{-17} m$^{-2/3}$), or strong ($> 2.5\times10^{-13}$ m$^{-2/3}$) [15].

2.2 Atmospheric Coherence Length r_0 and Seeing

Atmospheric coherence length [16] is the most common parameter for evaluating atmospheric impact on telescopes, describing image quality degradation. At the 1962 IAU meeting, astronomers posed two questions [14]: Could a single constant predict image quality degradation? Could a small telescope predict a large telescope' s performance? Fried [16] subsequently proposed the coherence length parameter to address these. Its definition is:

$$r_0=0.185\lambda^{6/5}\left(\sec z\int_0^\infty C_N^2(h)dh\right)^{-3/5}$$

where λ is wavelength and z is zenith angle. The coherence length $r_0=(\sec z)^{-3/5}$ decreases with increasing zenith angle. Seeing (in arcseconds), defined as the full width at half maximum of a stellar image, is:

$$R_0=0.98\frac{\lambda}{r_0}\times\frac{3600\times180}{\pi}$$

where λ is wavelength and r_0 is coherence length (converted from radians to arcseconds using 1 rad = 206,265). R_0 varies slowly with wavelength, with atmospheric effects diminishing at longer wavelengths. As summarized by Tony Travouillon [17] in Figure 4 [Figure 4: see original paper], telescope resolution versus wavelength shows that resolution increases with wavelength when turbulence dominates, but decreases when reaching the diffraction limit.

2.3 Atmospheric Coherence Time τ_0

τ_0, also called atmospheric frozen time, is based on Taylor' s frozen turbulence hypothesis [18], which states that wavefront distortions remain constant for a short duration—this timescale is τ_0. As shown in Figure 5 [Figure 5: see original paper], during this period turbulence doesn' t break into smaller eddies but is simply transported by wind. When $t > \tau_0$, observed stellar images change beyond what seeing can describe. Coherence time is critical for adaptive optics and interferometry; the system' s response time must be shorter than τ_0 for effective correction. Therefore, good astronomical sites should have low wind speeds to reduce control system requirements.

2.4 Isoplanatic Angle θ_0

The isoplanatic angle [14] defines the region where atmospheric turbulence is isotropic and locally homogeneous, producing identical phase distortions for wavefronts. It represents the maximum angular separation compensable by conventional adaptive optics; beyond this, correction fails. As shown in Figure 6 [Figure 6: see original paper], Star 1 requires phase correction $\phi_1 + \phi_3$, while Star 2 requires $\phi_2 + \phi_4$. Only when their angular separation is small can we approximate $\phi_1 \approx \phi_2$ and $\phi_3 \approx \phi_4$, enabling correction within the isoplanatic angle. Figure 7 [Figure 7: see original paper] shows that isoplanatic angle is larger when turbulence is near the ground and smaller when turbulence is at high altitude.

2.5 Turbulence Inner Scale l_0 and Outer Scale L_0

Reynolds' 19th-century turbulence experiments revealed that laminar flow becomes unstable at high velocities, transitioning to interfering vortices of various sizes (Figure 8 [Figure 8: see original paper]). When flow breaks into turbulence, eddies grow to a characteristic scale—the outer scale L_0—which generally ranges from meters to hundreds of meters [20]. L_0 values remain controversial, with measurements ranging from a few meters to 2 km depending on method (see Avila et al. [20] Table 1). However, all agree that when telescope diameter approaches or exceeds L_0, optical effects differ dramatically from traditional predictions. The outer scale then becomes unstable, breaking down and transferring kinetic energy to smaller scales until turbulence dissipates as heat and friction at the inner scale l_0, typically millimeter-scale. Turbulence between these scales is called the inertial subrange.

2.6 Scintillation Index σ^2

Atmospheric turbulence affects both wavefront phase and amplitude. Amplitude variations cause intensity fluctuations—the twinkling stars we observe. While scintillation index [17] has minimal impact on adaptive optics and interferometry, it becomes a significant error source for systems requiring high Strehl ratios, such as high-precision photometry.

3 Daytime Atmospheric Turbulence Profile Detection Methods

Turbulence measurement methods fall into two categories: (1) calculating turbulence characteristics from temperature and meteorological data, and (2) optical methods measuring either intensity scintillation or wavefront tilt. Non-optical methods for daytime profiling include acoustic radar (SNODAR) and radiosondes, enabling continuous day/night observations. Optical methods divide into wavefront tilt measurement (Solar SLODAR, SDIMM+, MOSP, PDSL, A-MASP) and intensity scintillation measurement (SHABAR, Solar SCIDAR).

3.1.1 Acoustic Radar

Acoustic radar [21-24] transmits a fixed-frequency sound wave into the atmosphere. Non-uniform temperature and wind velocity scatter the sound, and by observing backscatter characteristics (Figure 9 [Figure 9: see original paper]), we obtain spatial and temporal distributions of temperature and wind. Temperature is derived from backscatter power proportional to the square of the temperature gradient, while wind is measured via Doppler shift proportional to scatterer velocity. Proper radar configuration can also measure wind direction.

For SNODAR, the temperature structure constant [25] is:

$$C_T^2 = \frac{\sigma_{180} T^2}{4 \times 10^{-3} k^{-1/3}}$$

where σ_{180} is the effective backscatter cross-section per unit solid angle and scattering volume, T is absolute temperature, and k is acoustic wavenumber. The challenge lies in accurately obtaining σ_{180}:

$$\sigma_{180} = \frac{P_t E_t E_r P_r c\tau}{S_{ant} \exp(-2\alpha r)}$$

where P_t, E_t are electrical and acoustic radiation power, P_r, E_r are measured electrical and received acoustic power, c is sound speed, τ is pulse duration, r is distance to scattering volume, S_{ant} is antenna effective area, and α is atmospheric attenuation coefficient. The last two terms complicate measurement because α depends on acoustic frequency, temperature, and humidity.

After solving for C_T^2, the refractive index structure constant is:

$$C_N^2 = \left(\frac{80.1 \times 10^{-6} P}{T^2} \right)^2 C_T^2$$

where P is atmospheric pressure (hPa) and T is absolute temperature (K). SNODAR can also measure 3D wind profiles. When sound reflects from air moving at velocity V, its frequency f undergoes Doppler shift:

$$V = -\frac{c(f_s - f)}{2f_s}$$

where c is sound speed and f_s is scattered wave frequency. Vertical emission measures only vertical wind components; three transmitters in different directions are needed for 3D wind information, though array configurations are more common in practice.

SNODAR is robust for long-term automated monitoring with exceptional resolution (meter-scale). Since it uses sound rather than light, it operates continuously day and night, which is crucial for understanding turbulence evolution. However, rapid acoustic attenuation limits measurement range, requiring combination with other instruments for full atmospheric profiling. Data may be contaminated by other sound sources and nearby reflecting structures, though noise pollution is negligible at remote astronomical sites.

3.1.2 Radiosondes

Radiosondes [26–29] carry instruments through direct atmospheric contact, enabling precise parameter measurements. Common payloads include radiosondes (with temperature, humidity, pressure sensors) and microthermal sensors [30-33]. Radiosondes transmit measurement data to the ground, while microthermal sensors measure temperature variations across fine wires (30 m diameter) via unbalanced bridge and amplifier circuits, calculating near-surface optical turbulence from the resulting voltage signals. With response times <10 ms, these thin wires are vulnerable to wind damage.

Microthermal sensors can also be mounted on meteorological towers, limiting measurement height to tower elevation. Alternatively, balloons can be fixed while mechanical structures move sensors vertically to probe higher near-surface layers. Radiosonde drawbacks include: difficult recovery of landed instruments; expensive GPS units (required for landing prediction) that demand significant effort to retrieve; high costs (thousands to tens of thousands of yuan per disposable flight); long measurement times during which low-altitude turbulence may change; and uncertain ascent paths due to wind, causing large data fluctuations.

Recent drone developments promise to dramatically reduce sounding costs, potentially enabling drone-borne dropsonde measurements in the future.

3.2.1 SHABAR

SHABAR [34-36] typically consists of six scintillometers in a linear array, measuring turbulence below 500 m altitude. Each scintillometer probe has a detection range, and overlapping detection volumes at different heights produce correlated effects on both probes. Measuring these correlations enables inversion of turbulence at different layers to obtain the profile.

Using relative brightness fluctuations ($\Delta I/I$) between two probes separated by distance d, the covariance $CV(d)$ is:

$$CV(d) = 17.4\Omega^{-7/3}\lambda \cos^{-2/3}\zeta \int_0^{\infty} C_N^2(h)CV(h,d)dh$$

where $CV(h,d)$ is the covariance for a single turbulent layer at height h with probe separation d, Ω is solar angular diameter, λ is probe wavelength, and ζ is zenith distance. Least-squares fitting then yields the refractive index structure constant $C_N^2(h)$ and seeing.

Six scintillometers can divide the near-surface atmosphere into 15 layers. Scintillation results from averaging many independent sources; high-altitude sources become blurred through smoothing, reducing SHABAR' s sensitivity to high-altitude turbulence [38]. LUSCI (LUnar SCIntillometer array) [39] applies SHABAR principles at night, with recent developments providing references for daytime SHABAR. Nighttime measurement differs mainly in lunar phase variations, requiring guide cameras to measure moonlight intensity for hardware calibration. Nighttime also has more interference sources. SHABAR and LUSCI cannot be unified into one instrument because solar intensity far exceeds lunar intensity, requiring different hardware. Both have simple optical structures, are lightweight and inexpensive, making them ideal for early site survey campaigns. As shown in Figure 11 [Figure 11: see original paper], SHABAR is often installed alongside SDIMM [40] for simultaneous observations.

Recent LUSCI progress at Ali in 2020 used 48 detectors in six rings, achieving useful response heights of 1 km during full moon and 10 km during new moon. Though new moon intensity is lower, its smaller angular size produces larger intensity fluctuations that compensate effectively. Unfortunately, one ring' s failure reduced baselines from 16 to 11, with the longest baseline becoming 0.877 m, losing 500 m vertical resolution during full moon. Both devices provide near-surface turbulence profiles.

3.2.2 SLODAR, Solar SLODAR and SCIDAR, Solar SCIDAR

SLODAR [42, 43], proposed by Wilson in 2002 [44], measures layered atmospheric seeing and wind velocity. It uses a Shack-Hartmann wavefront sensor to measure wavefront slopes from two guide stars, reconstructing turbulence profiles through cross-correlation and autocorrelation of binary star wavefront slopes. Unlike SDIMM+ which uses covariance, SLODAR uses cross-correlation functions:

$$C(\delta i, \delta j) = \frac{\langle S_{i,j}(t) S_{i+\delta i, j+\delta j}(t) \rangle}{O(\delta i, \delta j)}$$

where $S_{i,j}(t)$ is the slope of the first guide star at wavefront sensor coordinate (i, j) at time t, $S_{i+\delta i, j+\delta j}(t)$ is the slope of the second guide star at coordinate $(i + \delta i, j + \delta j)$, and $O(\delta i, \delta j)$ counts all subaperture pairs separated by $(\delta i, \delta j)$.

The single-star autocorrelation function is:

$$A(\delta i, \delta j) = \frac{\langle S_{i,j}(t) S_{i+\delta i, j+\delta j}(t) \rangle}{O(\delta i, \delta j)}$$

In the absence of noise, the turbulence profile is obtained via:

$$\text{Profile} \propto F^{-1} \left[\frac{F[C]}{F[A]} \right]$$

where F and F^{-1} denote Fourier transform and inverse transform, yielding normalized turbulence profiles from 2D deconvolution.

As shown in Figure 12 [Figure 12: see original paper], for an isolated turbulent layer at height h_0, non-overlapping stellar paths prevent measurement. At height h_4, overlapping paths enable cross-correlation measurement between the right star' s signal in aperture i and the left star' s signal in aperture $i + 4$. Generally, turbulence height h_i is proportional to subaperture separation δw via $\delta h = \delta w / \theta$, where θ is the stellar separation angle. Thus, the number of turbulent layers depends on subaperture count, while maximum detectable height depends on farthest subaperture separation: $h_{n-1} = (n-1)\delta h \approx H_{max} = D/\theta$. Overlapping subapertures decrease with altitude, reducing correlation signals. Additionally, the movement speed and direction of cross-correlation peaks with time delay reveal wind velocity and direction at corresponding turbulent layers [46].

SCIDAR measures scintillation while SLODAR measures local wavefront tilt. SLODAR requires fewer photons (only enough for centroid calculation), enabling use of fainter binary stars near the zenith. However, SCIDAR offers higher resolution because scintillation autocorrelation functions have narrower peaks than wavefront tilt functions—scintillation spatial scales are smaller than phase scales, permitting higher resolution [47].

Both SLODAR and SCIDAR face similar limitations: telescope aperture and Shack-Hartmann subaperture count constrain atmospheric layering, and both have poor weak-turbulence detection capability. They also require large telescopes. Although a portable 400 mm SLODAR was developed in 2009, its maximum sampling height was only 2,000 m [48].

Solar SLODAR [49] adapts SLODAR for daytime by observing solar granulation, which conveniently covers the entire solar disk. However, low contrast makes processing more complex than for point sources. Two main differences from nighttime SLODAR exist: (1) the Sun is an extended source, not a point source; (2) numerous granulation sources are available.

Using extended sources instead of point sources makes aperture size height-dependent. Effective aperture increases with altitude, averaging out high-altitude turbulence effects and reducing wavefront tilt contributions. As shown in Figure 13 [Figure 13: see original paper], effective aperture is:

$$D_{eff} = D + h\theta$$

where θ is extended source size in radians, h is projected aperture height, and D is telescope aperture.

Solar SCIDAR [50] (Figure 14 [Figure 14: see original paper]) images the source at the focal plane after passing through the telescope. For small separation angles θ, two images overlap. To improve detection, two apertures are placed at the focal plane, followed by a virtual detection plane behind the focal length that separates the images, mimicking nighttime binary stars. Aperture size and separation are adjustable, yielding different separation angles $\theta = u_\alpha f$, where f is focal length and u_α is aperture separation. Measuring intensity fluctuations in both images and using cross-correlation methods then yields turbulence profiles.

Unlike nighttime SCIDAR's autocorrelation approach, Solar SCIDAR uses cross-correlation. Solar SCIDAR images consist of a weak core and strong halo, broadening correlation peaks and reducing high-altitude sensitivity. Additionally, the Sun’ s extended size beyond the apertures negatively impacts measurements.

3.2.3 PDSL

For adaptive optics, outer scale L_0 is an important parameter, motivating development of MOSP [51] to measure it. PML (Profiler of Moon Limb) [52] combines DIMM hardware with MOSP principles. PDSL [53] applies PML to daytime observations.

As shown in Figure 15 [Figure 15: see original paper], PDSL images the solar limb through turbulent layers onto two subapertures. Differential imaging eliminates telescope jitter errors. The transverse variance of wavefront arrival angle differences ϕ between two solar limb images is:

$$C_{\Delta\phi}(\theta) = \langle[\Delta\phi(\theta_0) \cdot \Delta\phi(\theta_0 + \theta)]\rangle$$

where $\Delta\phi(\theta_0) = \phi_T(\theta_0) - \phi_B(\theta_0)$ represents differences between matched points in top and bottom images, ϕ_T and ϕ_B are the solar limb wavefronts, and θ is the angular separation between point pairs (0 to full field of view).

Under the Von Karman model, the 2D spatial covariance correlation function is:

$$C_{\Delta\phi}(\theta) = \int_0^\infty C_N^2(h) K_a(B,h,\theta) dh$$

where h is turbulent layer height, B is subaperture center separation, and:

$$K_a(B,h,\theta) = 2\omega_\alpha(\theta h) - \omega_\alpha(B-\theta h) - \omega_\alpha(B+\theta h)$$

with:

$$\omega_\alpha(\varrho) = 1.19 \sec(z) \int_0^\infty f^2 \left(f^2 + \frac{1}{L_0^2(h)}\right)^{-11/6} [J_0(2\pi f\varrho) + J_2(2\pi f\varrho)] \left[\frac{2J_1(2\pi f D)}{2\pi f D}\right]^2 df$$

where z is zenith distance, f is spatial frequency, J_m is the m-th order Bessel function, $L_0(h)$ is outer scale function, and D is telescope aperture.

Considering different separation angles θ_j and height layers h_i, the full atmosphere can be expressed as:

$$C_\phi(\theta_j) = \sum_{i=0}^{N-1} \Delta h_i C_N^2(h_i) K_a(B, h_i, \theta_j)$$

where Δh_i is the thickness of turbulent layer at height h_i. Fixing outer scale L_0 allows solving for $K_a(B,h,\theta)$, then K_ϱ, and finally K_{C_N}. The matrix equation is:

$$Y = K_{C_N} \cdot C_N^2$$

where Y or $C_\phi(\theta)$ is measured covariance at different solar limb separations, K_{C_N} is the coefficient matrix, N is the number of reconstruction layers, and M is the number of angular separations θ.

In practice, measured values Y are obtained, and K_a can be calculated for selected heights and angles at fixed L_0, enabling solution of K_ϱ and K_{C_N}. A series of spatial covariances at different angles θ then inverts the turbulence profile. Small angular separations probe high altitudes, while large separations probe low altitudes, enabling high vertical resolution scanning of the upper atmosphere. PDSL is limited by field of view, preventing measurement below 100 m [53], but sub-100 m seeing can be obtained indirectly by subtracting PDSL' s >100 m seeing from SDIMM' s total seeing.

Based on PML and WMA-SDIMM [54, 55], Yunnan Astronomical Observatory developed PDSL for solar observations while maintaining nighttime lunar measurement capability, ensuring data continuity. Numerical simulations and experimental results have been obtained at Daocheng Wuming Mountain.

3.2.4 SDIMM+ and A-MASP

SDIMM+ [56] uses covariance analysis similar to DIMM. In the x-direction, image measurement covariance $C_x(s,a)$ is:

$$C_x(s,a) = 0.358\lambda^2 r_0(h_n)^{-5/3} D_{eff}(h_n)^{-1/3} F_x(s,a,h_n)$$

where:

$$F_x(s,a,h_n) = \alpha h_n^{-1/3} I\left(\frac{s}{\alpha h_n}, \frac{a}{\alpha h_n}\right)$$

From literature [57], the transverse $I(S,0) = [1 - 0.811 S^{-1/3}]$ and longitudinal $I(S,\infty) = [1 - 0.541 S^{-1/3}]$, where D_{eff} is the effective Shack-Hartmann subaperture diameter, s is subaperture pair separation (Figure 16 [Figure 16: see original paper]), and α is guide star angular separation. Measured covariance and calculable $F_x(s,a,h_n)$ enable fitting of seeing $r_0(h_n)$ at specific heights h_n via least squares.

SDIMM+ and Solar SLODAR have identical resolution when using the same wavefront sensor, differing only in analysis method (covariance vs. cross-correlation). SDIMM+ cannot measure wind speed or direction. Derived from DIMM, SDIMM+ is insensitive to telescope motion and tracking errors. Like SLODAR, it uses solar granulation as sources, requiring large telescopes for sufficient contrast.

To reduce dependence on large telescopes, Ren et al. proposed the Multiple-Aperture Seeing Profiler (MASP) [59] in 2015, using two small telescopes to address both large-aperture dependency and sampling height limitations, enabling use at sites without large telescopes. MASP' s two 400 mm telescopes each have 5-subaperture Shack-Hartmann sensors. Their separation simulates a large telescope with 14 subapertures, though issues include pointing, tracking, and jitter between telescopes. In 2016, A-MASP [60] improved this with two 100 mm telescopes, using multiple guide stars (8 \$×8$''to10''$×\$10 granulation regions) without requiring Shack-Hartmann sensors.

3.2.5 MISOLFA

MISOLFA (Moniteur d' Images Solaire Franco-Algerien) [61, 62] (Figure 17 [Figure 17: see original paper]) uses a Cassegrain telescope. Prism P1 at the entrance obtains two opposite horizontal solar limbs, whose beams reflect off primary mirror M1 to secondary mirror M2, then via small plane mirror M3 to the Nasmyth focus. A derotator presents two horizontal images to a filter selecting the desired band. Beam splitter P3 divides the beam: (1) to a CCD recording the solar limb (similar to PDSL but with opposite horizontal limbs), and (2) through a slit to prism P4 (composed of a beam splitter and 90° mirror) to photodiodes measuring flux and aperture images, where intensity fluctuations are proportional to wavefront arrival angle fluctuations. Optical fibers of different diameters at the aperture plane transmit signals to four photodiodes.

Method 2 primarily solves for coherence time. Method 1 uses a PDSL-like approach to fit $C_N^2(h)$ and $L_0(h)$ profiles, then derives other parameters. Through solar image processing, transverse covariance $C_{\alpha\perp}^{exp}(\theta)$ and structure function $D_{\alpha\perp}^{exp}(\theta)$ of wavefront arrival angles are extracted:

$$D_{\alpha\perp}^{exp}(\theta) = \frac{1}{N(\theta_m - \theta)} \sum_{k=1}^{N-\theta} [\alpha_\perp(k) - \alpha_\perp(k+\theta)]^2$$

where θ is angular separation in pixels, θ_m is maximum image range, N is number of sampled images, and $\alpha_\perp(k)$ is wavefront arrival angle fluctuation at point k.

The structure function $D_\alpha(\theta)$ is:

$$D_\alpha(\theta) = 2[\delta^2 - C_\alpha(\theta)]$$

where $C_\alpha(\theta)$ is covariance at different angular separations (see Equation 18) and $\delta^2 = C_\alpha(0)$ is wavefront arrival angle variance. Substituting yields:

$$D_\alpha(\theta) = 2.4 \sec(z) \int_0^\infty C_N^2(h) dh \int_0^\infty f^2 \left(f^2 + \frac{1}{L_0^2(h)}\right)^{-11/6} [J_0(2\pi f\theta) + J_2(2\pi f\theta)] \left[\frac{2J_1(2\pi f D)}{2\pi f D}\right]^2 df$$

Fitting then solves for $C_N^2(h)$ and $L_0(h)$ profiles.

4 Summary and Discussion

In summary, daytime atmospheric turbulence is more intense than nighttime due to solar radiation. The Sun' s extended nature also differs from nighttime point sources. As telescopes grow larger and systems more complex, whole-atmosphere detection no longer suffices. In new adaptive optics systems, detailed turbulence profiling is crucial. This review introduced several daytime turbulence profiling instruments. Table 2 and Figure 18 [Figure 18: see original paper] provide specifications for some daytime turbulence instruments. Meteorological devices offer indirect measurements with certain errors, while optical devices often require large telescopes that are scarce, and small devices lack sufficient precision and altitude range. Future development will likely focus on specialized daytime turbulence profilers for specific applications: compact, convenient devices for site selection, and fine-scale profilers for new adaptive optics systems.

References

[1] Babcock H W. PASP, 1953, 65: 229
[2] Seeing Forecast For Astronomical Purposes, https://weather.gc.ca/astro/seeing_e.html, 1998
[3] Kong Lin. PhD thesis, Chengdu: Institute of Optics and Electronics, Chinese Academy of Sciences, 2017: 13
[4] Rao C H, Zhang L Q, Kong L, et al. SCIENCE CHINA: Physics, Mechanics & Astronomy, 2018, 61: 8
[5] Kong L, Zhang L, Lei Z, et al. Chinese Optics Letters, 2016, 14: 6
[6] Zhang Lan-qiang. PhD thesis, Chengdu: Institute of Optics and Electronics, Chinese Academy of Sciences, 2014: 31
[7] Baba N, Isobe S, Norimoto Y, et al. Applied optics, 1985, 24: 1403
[8] Law N M, Mackay C D, Baldwin J E. A&A, 2006, 446: 739
[9] Hufnagel R E. Digest of Technical Papers, Topical Meeting on Optical Propagation through Turbulence. Amsterdam: Elsevier, 1974: 2
[10] Rao Rui-zhong. Modern Atmospheric Optics, Beijing: Science Press, 2012: 2
[11] Liu Li-yong, Yao Yong-qiang. Progress in Astronomy, 2010, 28: 13
[12] Quirrenbach A A. Extrasolar planets: Saas-Fee Advanced Course, 2006, 31: 137
[13] Yao Yuan-cheng. Master’ s thesis, Beijing: University of Chinese Academy of Sciences, 2013: 21
[14] Quirrenbach A. Progress in optics, Amsterdam: Elsevier, 1981: 290
[15] Song Teng-fei. PhD thesis, Chongqing: Chongqing University, 2018: 4
[16] Fried D L. JOSA, 1966, 56: 1380
[17] Travouilon T. Dissertation, Sydney: University of New South Wales, 2005: 44
[18] Fried D L. JOSA, 1965, 55: 1427
[19] Reynolds O. Philosophical Transactions of the Royal society of London, 1883, 174: 935
[20] Avila R, Ziad A, Borgnino J, et al. Journal of the Optical Society of America A, 1997, 14: 3070
[21] Lawrence J, Ashley M, Bonner C, et al. EAS Publications Series, 2007, 25: 31
[22] Bonner C S, Ashley M C B, Lawrence J S, et al. IAUSS, 2009, 47: 51
[23] Bonner C S, Ashley M C B, Lawrence J S, et al. Acoustics Australia, 2006,

7: 23
[24] Bonner C S, Ashley M C B, Lawrence J S, et al. Optical Turbulence: Astronomy Meets Meteorology. Singapore: World Scientific, 2010: 270
[25] Little C G. Proceedings of the IEEE, 1969, 57: 571
[26] Gavrilov N M, Luce H, Crochet M, et al. Annales Geophysicae: Copernicus GmbH, 2005, 23: 2401
[27] Luce H, Fukao S, Dalaudier F, et al. Journal of the Atmospheric Sciences, 2002, 59: 2885
[28] Xu Man-man, Shao Shi-yong, Liu Qing, et al. Acta Optica Sinica, 2020, 40: 14
[29] Xu Zi-qiang, Wu Xiao-qing, Xu Man-man, et al. Acta Physica Sinica, 2021, 70(24): 4204
[30] Li Xue-bao, Zheng Yan-fang, Xu Guang, et al. Modern Electronics Technology, 2012, 35: 128
[31] Wang Hong-shuai. Master' s thesis, Kunming: Yunnan Astronomical Observatory, Chinese Academy of Sciences, 2009: 15
[32] Holland W S, Robson E, Gear W K, et al. MNRAS, 1999, 303: 659
[33] Song T, Liu Y, Cai Z, et al. MNRAS, 2021, 505: 3070
[34] Beckers J M, Liu Z, Jin Z. Proceedings of SPIE, 2002, 4853: 273
[35] Hill F, Radick R, Collados M. ATST Site Survey Working Group Final Report, 2003, 14: 1
[36] Hartogensis O, Hammerschlag R, Sliepen G, et al. Solarnet IV: the Physics of the Sun from the Interior to the Outer Atmosphere, 2017: 102
[37] Beckers J M, Leon E, Mason J, et al. Solar Physics, 1997, 176: 23
[38] Liu Zhong, Lou Ke, Zhang Rui-long, et al. Astronomical Research & Technology, 2000, 4: 95
[39] Tokovinin A, Bustos E, Berdja A. MNRAS, 2010, 404: 1186
[40] Zhong L, Beckers J M. Solar Physics, 2001, 198: 197
[41] Hickson P, Feng L, Hellemeier J A, et al. MNRAS, 2020, 494: 5992
[42] Goodwin M, Jenkins C, Lambert A. PASP, 2013, 30: 18
[43] Butterley T, Wilson R W, Sarazin M. MNRAS, 2010, 369: 835
[44] Wilson R W. MNRAS, 2002, 337: 103
[45] Mazzoni T, Busoni L, Bonaglia M, et al. Adaptive Optics Systems V. Bellingham: International Society for Optics and Photonics, 2016: 99093
[46] Wang Zhi-yong. PhD thesis, Chengdu: Institute of Optics and Electronics, Chinese Academy of Sciences, 2019: 28
[47] Shepherd H W, Osborn J, Wilson R, et al. MNRAS, 2014, 437: 3568
[48] Wilson R W, Butterley T, Sarazin M. MNRAS, 2009, 399: 2129
[49] Townson M J. Dissertation, Durham: Durham University, 2016: 94
[50] Miura N, Oh-Ishi A, Shionoya S, et al. MNRAS, 2013, 434: 1205
[51] Maire J, Ziad A, Borgnino J, et al. MNRAS, 2007, 377: 1236
[52] Chabe J, Aristidi E, Ziad A, et al. Applied optics, 2020, 59(25): 7574
[53] Song T F, Cai Z C, Liu Y, et al. MNRAS, 2020, 499: 1909
[54] Liu Y, Li X B, Zhang X F, et al. Observatory Operations: Strategies, Processes, and Systems VII, Bellingham: International Society for Optics and Photonics, 2018: 22

[55] Song T F, Wen Y M, Liu Y, et al. Solar Physics, 2018, 293(2): 1
[56] Scharmer G B, Van Werkhoven T I M. A&A, 2010, 513: A25
[57] Sarazin M, Roddier F. A&A, 1990, 227: 294
[58] Yang Feng, Zhao Gang, Ren De-qing. Acta Astronomica Sinica, 2019, 60: 51
[59] Ren D, Zhao G, Zhang X, et al. PASP, 2015, 127: 870
[60] Ren D, Gang Z. PASP, 2016, 128: 105002
[61] Ikhlef R, Corbard T, Morand F, et al. MNRAS, 2016, 458: 517
[62] Ikhlef R, Corbard T, Irbah A, et al. EAS Publications Series, 2012, 55: 369

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