SLODAR System Development for Vertical Atmospheric Disturbance Profiling at Geochang Observatory

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Implemented at the Geochang Observatory in South Korea, our slope detection and ranging (SLODAR) system features a 508 mm Cassegrain telescope (f/7.8), incorporating two Shack-Hartmann wave-front sensors (WFS) for precise measurements of atmospheric phase distortions, particularly from nearby binary or double stars, utilizing an 8 × 8 grid of sampling points. With an ability to reconstruct eight-layer vertical atmospheric profiles, the system quantifies the refractive index structure function (Cₙ²) through the crossed-beam method. Adaptable in vertical profiling altitude, ranging from a few hundred meters to several kilometers, contingent on the separation angle of binary stars, the system operates in both wide (2.5 to 12.5 arcminute separation angle) and narrow modes (11 to 15 arcsecond separation angle), covering altitudes from 122.3 to 611.5 meters and 6.1 to 8.3 kilometers, respectively. Initial measurements at the Geochang Observatory indicated Cₙ² values up to 181.7 meters with a Fried parameter (r₀) of 8.4 centimeters in wide mode and up to 7.8 kilometers with an r₀ of 8.0 centimeters in narrow mode, suggesting similar seeing conditions to the Bohyun Observatory and aligning with a comparable 2014–2015 seeing profiling campaign in South Korea.

Keywords : Adaptive optics, Atmospheric turbulence, Fried parameter, Refractive index structure function (Cₙ²), SLODAR

OCIS codes : (010.1330) Atmospheric turbulence; (120.4640) Optical instruments; (220.1080) Active or adaptive optics; (350.1260) Astronomical optics

1. INTRODUCTION

Many observatories that operate adaptive optics (AO) use vertical atmospheric turbulence profiling for site evaluation, adaptive optics design and operation, and optimization [1–6]. In addition, real-time vertical turbulence profiling is also required for various AO algorithms, such as three-dimensional (3D) tomography wavefront reconstruction, optimal conjugate altitude search, and image post-processing tasks related to point spread function reconstruction. As a result, real-time vertical atmospheric turbulence profiling is very important for AO [7–9].

There are several instruments for measuring atmospheric turbulence profiles, each with its own advantages and limitations in terms of cost, vertical resolution, altitude range, and ease of implementation [9–18]. These include slope detection and ranging (SLODAR) [9–13], scintillation detection and ranging (SCIDAR) [14–16], differential image motion monitor (DIMM) [17, 18], and multi-aperture scintillation sensor (MASS) [17]. Especially, the SLODAR

There are several astronomical observatories in Korea, including the Bohyun and Geochang Observatories [19, 20]. Notably, the Bohyun Observatory is home to Korea’s largest ground-based 1.8 m telescope, while the Geochang Observatory is dedicated to satellite laser ranging with a 1.0 m SLR telescope [20]. Regarding astronomical seeing evaluation, there are several reports on the Bohyun Observatory, including a seeing campaign carried out with a similar SLODAR system as reported herein for one year starting in June 2014 [21, 22]. However, there are no reports on atmospheric seeing evaluation at the Geochang Observatory, which is essential for further improvement in measurement accuracy, potentially aided by the use of adaptive optics [23, 24]. In response to this gap, we have taken the initiative to develop and install an atmospheric vertical seeing profiler utilizing a SLODAR for the Geochang Observatory.

In Section 2, we present a comprehensive overview of SLODAR technology and its development. Section 3 reports on the initial observation results, and Section 4 serves as the concluding section for this paper.

II. SLODAR DEVELOPMENT

2.1. Principles

In 2002, Wilson proposed the SLODAR method, a technique reconstructing vertical optical turbulence profiles through cross-covariance measurements from two Shack-Hartmann wave-front sensors (WFS) measurements for a pair of nearby stars, known as the crossed-beam method [10]. Figure 1 illustrates the schematic concept of the crossed-beam method. Within this technique, the vertical resolution ($\delta h$) and the maximum measurement altitude ($H_{\text{max}}$) are defined as follows:

\[ \delta h = \omega / \theta, \]

\[ H_{\text{max}} = (N - 1) \times \delta h, \]

where $\theta$ represents the angular separation of the stars, and $\omega$ is the size of the sub-aperture in the wavefront sensing. $N$ denotes the number of sub-apertures. Increasing the separation angle of the binary stars enhances vertical resolution but reduces the maximum altitude [9–13].

The SLODAR consists of a telecentric lens, a prism mirror, and two WFSs, and is attached to the rear end of the telescope. The prism mirror reflects the binary stars at a 45° onto the WFSs. Each WFS is composed of a collimating lens, a micro lens array (MLA), and an electron multiplying-charge coupled device (EM-CCD). Figure 2 shows the optical schematic of the SLODAR.

In the crossed-beam method, the number of turbulence profiling layers is determined by the number of sub-apertures on the WFS laid in the telescope pupil, and the altitude is determined by the separation angle of the binary star. SLODAR operates in two modes based on this separation angle: The wide mode for measuring turbulence at lower altitudes and the narrow mode for higher altitudes [13]. In the narrow mode, where the separation angle is very narrow, binary stars cannot be separated using a prism mirror, so two focal points are placed per MLA pitch using a single WFS. For the wide mode, the binary stars can be sufficiently separated by the prism mirror, placing one focal point per MLA pitch, and utilizing two WFSs. Figures 3 and 4 show the optical layouts and WFS images for both modes.

In the crossed-beam method, the layer turbulence profile is reconstructed from the cross-covariance of the binary star phase slope, while the overall turbulence profile is reconstructed from the auto-covariance of the single star phase slope [13]. The formulas for cross-covariance and auto-covariance are as given by:

![FIG. 1. Schematic diagram illustrating the crossed-beam method. This specific diagram depicts the construction of 8 layers of vertical profiling with 8 sub-aperture wavefront sensing [13].](image)

![FIG. 2. Optical schematic of the SLODAR [13].](image)
\[ C(\delta i, \delta j) = \langle \sum_{i,j} s_{i,j}(t) s'_{i+\delta i,j+\delta j}(t) / O(\delta i, \delta j) \rangle, \]  
\[ A(\delta i, \delta j) = \langle \sum_{i,j} s_{i,j}(t) s_{i+\delta i,j+\delta j}(t) / O(\delta i, \delta j) \rangle. \]

Here, ensemble \( \langle \rangle \) refers to the average over frames and \( s_{i}(t) \) denotes the slope of the sub-aperture \((i, j)\) at time \( t \). \( s' \) represents the slope of the second star, and \( O(\delta i, \delta j) \) denotes the number of overlapped pixels for \((\delta i, \delta j)\). Finally, the measured covariance can be compared with the reference covariance applied with the Kolmogorov model to estimate the atmospheric turbulence profile.

### 2.2. Initial Design

The SLODAR’s initial design is crucial to the overall performance and efficiency of the system. The initial design of SLODAR, which includes the selection of the collimating lens and MLA, can be conducted based on the specifications of the telescope and EM-CCD. We utilized a corrected Dall-Kirkham (CDK) type telescope with a diameter of 508 mm and an EM-CCD known for its extremely low spurious noise. Tables 1 and 2 summarize the specifications of the telescope and the EM-CCD, respectively [25, 26].

We require a collimated beam size of MLA pitch \( \times \) 8 at the WFS to measure an 8-layer atmospheric profile. The collimating lens focal length can be determined by considering the collimated beam diameter, denoted as \( D_{C,B} \), and the telescope F-number, represented as \( F/#_{Tele} \).

\[ f_{\text{coll}} = F/#_{\text{Tele}} \times D_{C,B}. \]

The MLA can be optimally selected by considering the sampling ratio in the WFS. To calculate the sampling ratio, which is the number of pixels per FWHM (Full Width at Half Maximum), both the diffraction limited FWHM and the WFS image scale are required. The diffraction limited FWHM can be calculated using the diameter of the sub-aperture, denoted as \( \omega \), and the wavelength [24]. \( D.L. \) represents the diffraction limit in arcsec units, and \( \lambda \) corresponds to the V-band (550 nm) [13].

\[ D.L. = 206265 \times 1.22 \times \lambda / \omega. \]

#### TABLE 1. Telescope specifications [25]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>CDK 20</td>
</tr>
<tr>
<td>Type</td>
<td>CDK</td>
</tr>
<tr>
<td>Primary Mirror Diameter (mm)</td>
<td>508</td>
</tr>
<tr>
<td>Secondary Mirror Diameter (mm)</td>
<td>191</td>
</tr>
<tr>
<td>Focal Ratio</td>
<td>( f/7.77 )</td>
</tr>
<tr>
<td>Focal Length (mm)</td>
<td>3,951</td>
</tr>
<tr>
<td>Back Focal Length (mm)</td>
<td>269</td>
</tr>
<tr>
<td>Image Scale (arcsec/mm)</td>
<td>52.2</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>63.5</td>
</tr>
</tbody>
</table>

#### TABLE 2. EM-CCD specifications [26]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Andor iXon Life 897</td>
</tr>
<tr>
<td>Active Pixels</td>
<td>( 512 \times 512 )</td>
</tr>
<tr>
<td>Pixel Size (µm)</td>
<td>( 16 \times 16 )</td>
</tr>
<tr>
<td>Active Pixel Well Depth</td>
<td>180,000 e-</td>
</tr>
<tr>
<td>Gain Register Pixel Well Depth</td>
<td>800,000 e-</td>
</tr>
<tr>
<td>Max Readout Rate (MHz)</td>
<td>17</td>
</tr>
<tr>
<td>Frame Rate (fps)</td>
<td>56</td>
</tr>
<tr>
<td>Readout Noise (( N_d ))</td>
<td>&lt;1 e-</td>
</tr>
<tr>
<td>Dark Current (( N_d ))</td>
<td>0.0003 e-/pix/sec</td>
</tr>
</tbody>
</table>
The $I.S_{\text{WFS}}$ represents the WFS image scale in arcsec/pixel, and the sampling ratio, denoted as $S.R.$, can be calculated by dividing the $D.L.$ by the $I.S_{\text{WFS}}$. $P$ represents the pixel size.

\[
I.S_{\text{WFS}} = I.S_{\text{Tele}} \times P \times f_{\text{coll}} / f_{\text{MLA}},
\]

(7)

\[
S.R. = 0.5 \times D.L./I.S_{\text{WFS}}.
\]

(8)

A sampling ratio of approximately 1.5 is suitable for centroid calculation [27]. The collimating lens was selected with a focal length of 30 mm, and the MLA was chosen with a pitch of 500 µm and a focal length of 32.8 mm.

### 2.3. Optimization

Sufficient illumination is required in the WFS images for centroid computation. Considering the obstruction, it is necessary to use more than 40 focal points with sufficient illumination in the $8 \times 8$ MLA area. We determined the collimated beam diameter to be approximately 4.25 mm to ensure that the illumination was above 0.7 for more than 40 focal points. Illumination can be verified through the coordinates on the MLA plane represented by $x$, and the radius of the collimated beam represented by $r$.

\[
\text{Illumination} = \int_{x_1}^{x_2} \sqrt{x^2 - r^2} \, dx.
\]

(9)

In the SLODAR design, telescope telecentricity is essential [13]. Using Eq (4), the Focal ratio including the telecentric lens can be determined. We designed the telecentric lens to achieve a Focal ratio of $f/7.06$. Figure 5 shows the optical schematic of the SLODAR without the prism mirror and the illumination of the 40 focal points observed on the MLA plane.

Additionally, for accurate altitude turbulence measurements, conjugation is required between the MLA and the telescope pupil. Without conjugation, the turbulence strength measured at the ground (0 m) could have an error of several meters from the actual altitude. The conjugation design was carried out by placing the MLA at a stop pupil position.

The optimized SLODAR can determine the observable separation angle of binary stars. The dimensions of the prism mirror determine the range of separation angles for binary stars observable in wide mode. In narrow mode, the range of observable separation angles for binary stars is determined by the MLA pitch. The determined separation angles are 2.5–12.5 arcmin for wide mode and 11–15 arcsec for narrow mode. Figure 6 shows the final developed SLODAR, and Table 3 presents the SLODAR specifications.

### 2.4. Observation

The operation of the SLODAR system proceeds in the following order: Checking ambient conditions, selecting, and pointing to the target, and data measurement.

The observer must ensure that two conditions are satisfied (humidity < 70% and wind speed < 13 m/s) before opening the dome. High humidity can cause dew to form on the optical system, and strong winds can cause the telescope to shake, making observation difficult [13].

![FIG. 6. Telescope and SLODAR image.](image-url)

![FIG. 5. SLODAR design: (a) SLODAR optical schematic without the prism mirror, and (b) illumination on the micro lens array (MLA) plane.](image-url)

<table>
<thead>
<tr>
<th>Target Separation</th>
<th>Wide Mode</th>
<th>2.5–12.5 arcmin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow Mode</td>
<td>11–15 arcsec</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No. of Measurements Layer</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD Exposure Time (ms)</td>
<td>3</td>
</tr>
<tr>
<td>(Frame Rate: 56 Hz)</td>
<td></td>
</tr>
<tr>
<td>Minimum Elevation (°)</td>
<td>45</td>
</tr>
<tr>
<td>Minimum Moon-target Separation (°)</td>
<td>15</td>
</tr>
</tbody>
</table>
After opening the dome, the operator should select and point to the target. The target is chosen from a list of binary stars, which has been compiled from the Tycho-2 star catalogue and the Washington double star catalogue, containing observable binary stars. The list of binary stars primarily used at the Geochang SLR Observatory is presented in Table 4, and the observation conditions are as follows:

1) Binary stars within the target separation range,
2) Binary stars with an apparent magnitude of 7 or less,
3) Binary stars located more than 15 degrees from the moon,
4) Binary stars with an elevation angle of 45 degrees or higher.

After selecting and pointing to the target, we begin measuring the slope using binary stars. When using wide mode, we measure the slope from each of the two WFS. In narrow mode, we measure the slopes from a single WFS. For narrow mode, the MLA pitch is divided horizontally into two sections, and the slope is measured for each area. The exposure time during measurement is 3 ms, and we store the slope data in packets, with each packet containing 1,000 frames. If the target’s elevation angle drops below 45 degrees or if observation becomes difficult, we switch to a different target and resume measurement.

III. FIRST OBSERVATION RESULTS

3.1. Site Description

The Geochang SLR Observatory is located on the top of Mt. Gamak, which is located near to the city of Geochang, Gyeongsangnam-do, South Korea. Its coordinates are 35°35’24.0”N 127°55’12.0”E, and it stands at an elevation of 952 meters. Figure 8 shows the location of the Geochang SLR Observatory.

The observatory often receives heavy fog from late spring through early autumn due to its proximity to a fully filled water reservoir located 3.5 kilometers away. Especially from June to September, the average humidity exceeds 70%, and high precipitation imposes limitations on observations. As a result, the primary period for observations at the observatory is mainly from late autumn to mid-spring.

Table 4 presents the monthly variation of the main me-

<table>
<thead>
<tr>
<th>Mode</th>
<th>Binary Star ID</th>
<th>Separation Angle</th>
<th>( H_{\text{max}}(\delta h) ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wide Mode</strong></td>
<td>03-02a</td>
<td>3.3’</td>
<td>458.9 (65.6)</td>
</tr>
<tr>
<td></td>
<td>08-13a</td>
<td>8.4’</td>
<td>181.7 (25.9)</td>
</tr>
<tr>
<td></td>
<td>10-10a</td>
<td>10.2’</td>
<td>150.3 (21.5)</td>
</tr>
<tr>
<td><strong>Narrow Mode</strong></td>
<td>STF1962</td>
<td>11.7”</td>
<td>7,836.3 (1,119.5)</td>
</tr>
<tr>
<td></td>
<td>STF331</td>
<td>12.0”</td>
<td>7,640.4 (1,091.5)</td>
</tr>
<tr>
<td></td>
<td>STF2280AB</td>
<td>14.3”</td>
<td>6,411.5 (915.9)</td>
</tr>
</tbody>
</table>

FIG. 7. SLODAR system overview: (a) Telescope, (b) SLODAR, (c) workstation, and (d) dome.

FIG. 8. Geochang SLR Observatory location on maps.
metrical conditions in Geochang. This graph is derived from 30 years of historical observation data by the Korea Meteorological Administration (KMA) from 1992 to 2022 [28]. These results are very similar to the meteorological conditions at the Bohyun Observatory.

3.2. Initial Observation

We conducted initial observations at the Geochang SLR Observatory on June 16, 2023, utilizing wide and narrow measurement modes. The observations were conducted sequentially, with a 1-hour separation, over 30 minutes each. In the wide mode, observations were performed with a binary star of 8.4' angular separation (ID 08-13a) from 21:30 to 22:00 local time. Subsequently, narrow mode observations were conducted from 23:00 to 23:30 local time with a binary star of 11.7" angular separation (STF 1962). Figure 10 displays the sampled auto-covariance and cross-covariance for the wide binary star (ID 08-13a) with two components referred to as left and right, as defined in Eqs. (3) and (4).

From each observation, ten mean turbulence profiles were derived over 3 minutes using the method described in Section 2.1. Throughout this period, the statistical properties of atmospheric disturbance can be considered as not varying.

Firstly, Fig. 11 illustrates the measured Fried parameter \( r_0 \) for both wide and narrow modes. The average values over 30 minutes are 8.8 cm for the wide mode and 8.4 cm for the narrow mode. This suggests that the overall seeing strength did not change significantly during the two hours of observation. The number of observations is too few to reach any conclusions. However, regarding the overall seeing strength in terms of the Fried parameter \( r_0 \), the mean value at the SLR site aligns well with the statistical distribution of the seeing conditions observed at the Bohyun Observatory, which has a mean value of 8.28 cm with a standard deviation of 2.25 cm [21].

Secondly, Fig. 12 displays ten \( C_n^2 \) profiles along with their mean profile obtained from the wide mode. The wide mode allowed us to capture detailed \( C_n^2 \) vertical profiles.

FIG. 9. Monthly variations of temperature, precipitation, and humidity of Geochang: (a) Recent 30-year average temperature and precipitation graph, (b) recent 30-year average humidity graph.

FIG. 10. Sampled auto-covariance and cross-covariance of the wide binary star (ID 08-13a).

FIG. 11. Initial measurements of Fried parameter \( r_0 \) using wide and narrow measurement modes, sequentially over 30 minutes each. Each data point represents the mean value over 3 minutes.
near the ground, a crucial aspect for wide-field AO or ground AO imaging. The specific measurement covered an altitude range of 181.1 meters with an increment of 25.9 meters. The results indicate that the most significant atmospheric disturbance occurs around the ground layer, with a few weaker layers observed around 50 meters in altitude.

Similarly, Fig. 13 displays ten $C_n^2$ profiles along with their mean profile obtained from the narrow mode. The narrow mode enabled the capture of overall $C_n^2$ vertical profiles up to 5–10 km, providing crucial information for estimating the scintillation effect caused by high wind speeds around high altitudes. The specific measurement covered an altitude range of 5.7 kilometers with an increment of 814 meters. The narrow mode measurement also confirmed that the most significant atmospheric disturbance occurs around the ground layer. However, it revealed a few weaker layers observed around 4 km and 6 km altitudes.

IV. CONCLUSION

We developed the SLODAR system at the Geochang SLR Observatory in South Korea to characterize turbulence profiles. The SLODAR system, featuring a 508 mm Cassegrain telescope, reconstructs an eight-layer vertical atmospheric profile. Initial observations were conducted at the Geochang SLR Observatory on June 16, 2023, operating in both wide and narrow modes for 30 minutes each. The average Fried parameter over 30 minutes is 8.8 cm for the wide mode and 8.4 cm for the narrow mode. Additionally, strong turbulence was found in the ground layer for both modes. These findings indicate similar observational conditions to those at the Bohyun Observatory, and we plan to continue real-time vertical atmospheric turbulence profiling at the Geochang SLR Observatory for over a year.

FUNDING

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DISCLOSURES

The authors declare no conflicts of interest.

DATA AVAILABILITY

Data underlying the results presented in this paper are not publicly available at this time, but may be obtained from the authors upon reasonable request.

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