Robotic SLODAR development for seeing evaluations at the Bohyunsan Observatory

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ABSTRACT

We developed a robotic SLODAR (SLOpe Detection And Ranging) system for the characterization of vertical profiles of atmospheric optical turbulence at the Bohyunsan Observatory in South Korea. SLODAR was developed through a partnership between Kongju National University of South Korea and Durham University of the U.K. The SLODAR instrument is installed into a 50cm Cassegrain telescope focus. The telescope feeds incoming star light into a pair of Shack-Hartmann wavefront sensors. A SLODAR analysis of the wavefront sensor data yields turbulence profiles of the surface layer of turbulence, with the vertical resolution depending on the separation and elevation of the target stars. The robotic operation of SLODAR is conducted by a supervisor located at Kongju National University, 240 km away from the observatory (a 4~5 hour drive) only when the environmental conditions are suitable for observation, based on data from a nearby weather station, real-time satellite weather images, and on-site personnel communications. After the installment, the seeing profiles were recorded for more than 30 nights, confirming that the ground layer (<30m) is strongly dominant with regard to seeing and that the total seeing Fried parameter at 500 nm is 8.28 cm with a standard deviation of 2.25 cm. These results are superior to previously reported seeing values at the site.

1. INTRODUCTION

Korea's largest 1.8 m telescope is located on the Bohyunsan Optical Astronomy Observatory (BOAO) or the Korea Astronomy & Space Science Institute (KASI). Every year, KASI publishes annual astronomical seeing statistics based on scientific instrumental observations [1-2], but not based on seeing monitoring instruments such as DIMM (Differential Image Motion Monitor) [3], SCIDAR (SCIntillation Detection And Ranging) [4], or SLODAR (SLOpe Detection And Ranging) [5]. The reported astronomical seeing values (2.1~2.3″ mean) have been apparently worse than the typically expected values, most likely due to the presence of residual telescope and instrumental aberrations, along with dome seeing. Yuk reported seeing measurements at BOAO using a small telescope DIMM in 2003 [6], but the reported measurement time was too short (less than 5 minutes) to reach any meaningful conclusions. In 2013, Kongju National University in South Korea and Durham University in the U.K. started an international campaign to characterize optical turbulence at BOAO with a SLODAR instrument. In June of 2014, a SLODAR instrument with 50 cm telescope was installed, and it has operated for just over a year as of the time of this writing. This paper introduces the SLODAR system and measurements from its first year.

2. SITE DESCRIPTION

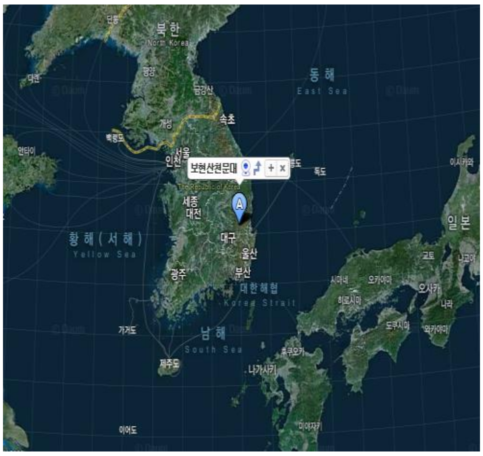
2.1 General introduction

The Bohyunsan Optical Astronomy Observatory (BOAO) was established in 1996 with a 1.8 m reflecting telescope, the largest optical telescope in Korea. A CCD imaging system was developed for the observatory, a 1k CCD IS, in 1996, followed by a 2k CCD IS in 1999 and a 4k CCD IS for observations. The year 2003 witnessed the successful development of the high-dispersion Bohyunsan Optical Echelle Spectrograph (BOES) [7]. Including its spectropolarimetry functions, BOES is now internationally recognized as among the most outstanding of high-dispersion spectrographs in its class. In 2008, its capabilities were further upgraded when the KASI Near-Infrared Camera System (KASINICS) was developed and installed for use with the 1.8 m telescope system [8].

BOAO operates the 1.8 m telescope and three instruments (BOES, KASINICS, and 4K CCD camera) during the observing season, except for the maintenance period of July to August. BOAO announces observation proposals twice a year, in May and in October. During the observing periods, observations are generally performed for approximately 120 nights out of nearly 300 effectively scheduled, though not all are photometric. BOAO supports approximately 50 observing programs of KASI and other institutes yearly and produces corresponding research results which are published regularly in SCI journals [1].

2.2 Site location

The observatory is located on the top of Mt. Bohyun, which is located near to the city of Youngcheon, Kyungsangbuk-do, South Korea. The coordinates are 36°09'53.19"N 128°58'35.68"E 1124 m. The observatory is 83 km away from Mt. Choejong, where the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) site was located until it closed in 1993 due to weather and cost concerns [9]. Because a fully filled water reservoir is located 2.6 km away from the observatory, the observatory receives severe fog from late spring to early autumn. Therefore, the observation window of the observatory is mainly from late autumn to the middle of spring.



a) Location on a large-scale map

b) Location on a medium-scale map

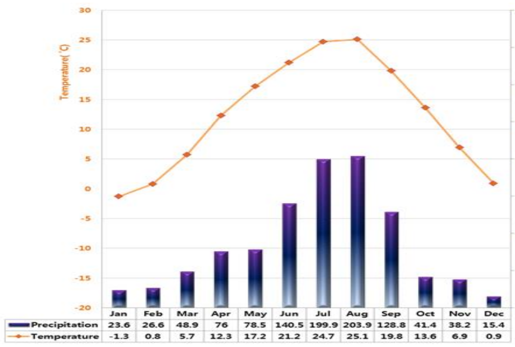
Figure 1. BOAO location on maps of two different scales

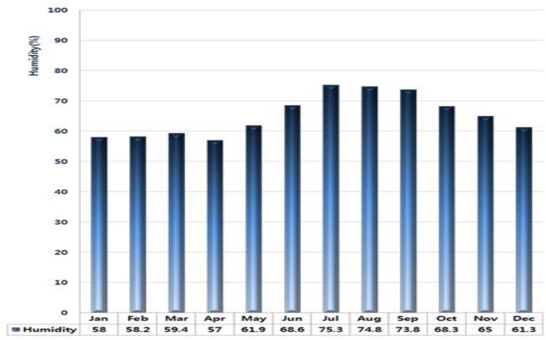
2.3 General weather conditions

Table 1 lists the monthly variations in the major weather conditions of Youngcheon city. The data are derived from past observations of the Korea Meteorological Administration (KMA) over 30 years, from 1981 to 2010 [10]. Figure 2 plots the monthly variations of the temperature, precipitation and humidity. As shown in Table 1 and Fig. 2, the humidity exceeds 70% from June to September (sometimes extending into October) such that ground fog severely hinders observations from late spring to early autumn, as mentioned above.

Table 1. Monthly Variations in Major Weather Conditions (averages of 30 years)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean Temp (°C)	-1.3	0.8	5.7	12.3	17.2	21.2	24.7	25.1	19.8	13.6	6.9	0.9
Max Temp (°C)	5.0	7.7	12.8	19.8	24.5	27.3	29.5	30.3	26.0	21.4	14.2	7.6
Min Temp (°C)	-6.4	-4.5	-0.2	5.0	10.4	15.9	20.6	21.0	15.1	7.4	0.7	-4.6
Precipitation (mm)	23.6	26.6	48.9	76	78.5	140.5	199.9	203.9	128.8	41.4	38.2	15.4
Mean wind speed (m/s)	2.3	2.1	2.1	2.0	1.8	1.6	1.5	1.4	1.3	1.4	1.7	2.1
Mean Humidity(%)	58.0	58.2	59.4	57.0	61.9	68.6	75.3	74.8	73.8	68.3	65.0	61.3
Fog continuous time(hr)	4.58	4.48	4.37	10.12	10.62	11.98	8.48	13.18	30.45	27.08	15.29	9.37
Cloud Amount(%)	35	41	51	48	52	66	69	63	59	44	39	31





a) Temperature & precipitation b) Humidity

Figure 2. Monthly variations of temperature & precipitation and humidity (averages of 30 years)

3. SLODAR INSTRUMENT

3.1 **Instrument Overview**

SLODAR refers to a cross-beam method based on observations of double stars using a Shack-Hartmann wavefront sensor. The optical turbulence profile is recovered from the cross-correlation of the wavefront slope measurements of two stars [5, 11].

An automated SLODAR system is based on a 50 cm reflecting telescope, as specified in Table 2, on a network-controlled German equatorial mount. The SLODAR instrument developed by Durham University is installed at the Cassegrain focus. The telescope feeds incoming star light into a pair of Shack-Hartmann wavefront sensors. A SLODAR analysis of the wavefront sensor data yields turbulence profiles of the surface layer of the turbulence, with the vertical resolution depending on the separation and elevation of the target stars. The instrument has two observing modes, "wide" and "narrow." In the narrow mode, very narrow targets (10~15 arcsec) are measured to provide the turbulence profile with coarse resolutions, up to a maximum sensing altitude of 6km. In the wide mode regime, relatively wide targets are chosen (from nearly 3.3 to 12 arcmin) such that the ground layer profile is measured up to nearly 500m. Figure 3 shows images of the dome and telescope with the instrument at the Bohyun Observatory. Table 3 lists the system specifications.

The system is remotely controlled by a supervisor located at Kongju National University, 240 km away from the observatory (a 4~5 hr drive). Remote observation is conducted when the environmental conditions are suitable for observation based on data from a nearby weather station, real-time weather satellite images, and on-site personnel communications. Due to the possible absence of personnel at the site, operations are carried out with relatively high safety standards. One of the prime requirements pertains to the humidity level; i.e. it should be lower than 70% to protect the instrument.

Table 2. Telescope Specifications

Model	RC 500
Type	Ritchey Chretien
Primary mirror diameter	500 mm
Optical system	1/5 λ ptv , 1/30 λ RMS
Focal length	5000 mm
Focal ratio	F / 10
Weight	75kg
Diffraction limited and over field radius	0.15 °
Secondary obscuration diameter	180 mm

a) Dome

b) Telescope with the SLODAR instrument

Figure 3. Images of the dome and telescope with the SLODAR instrument at the Bohyun Observatory

Table 3. SLODAR System Specifications

Requirement	Specification	Comments
Target star separation	10-15 arcsec, 2-12 arcmin	Any extra range to be at the wide end of the range
Limiting magnitude	6.5	
CCD exposure time	3 ms	Frame rate 57.6 Hz
Minimum elevation	45 degrees	
Maximum wind speed	13 m/s	
Declination range	-10 to +70 degrees	
Sun elevation limit	-10 degrees	
Minimum moon-target separation	15 degrees	

3.2 **Targets**

As discussed above, the vertical resolution depends on the separation and elevation of the target stars. Table 3 shows how the maximum sensing height and the extent of the lowest resolution element vary with the target separation.

Table 4. Vertical Resolution as a Function of the Target Separation

Target separation (arcmin)	Zenith		45 degree elevation	
	First bin width, dh/2 (m)	Maximum sensing height (m)	First bin width, dh/2 (m)	Maximum sensing height (m)
0.167	644	9024	456	6380
0.25	430	6016	304	4253
2	53.7	752.0	38.0	531.7
3	35.8	501.3	25.3	354.4
6	17.9	250.7	12.7	177.2
9	11.9	167.1	8.4	118.1
12	9.0	125.3	6.3	88.6

4. OBSERVATIONS THUS FAR

4.1 **Overview**

SLODAR has operated for approximately a year thus far as of the time of this writing and has accumulated seeing profiles for approximately 30 nights. The small number of observation nights is due to its stringent operational requirements and also due to the poor weather conditions at the observatory.

Figure 4 shows the typical humidity variations over one month (Nov. 2014). There were 12 nights when the humidity was lower than 70%, at which level SLODAR is allowed to operate, as mentioned in section 3.1. However, clouds in the sky reduced the number of observable nights to 5, as plotted in Figure 5. It should be noted that the 1.8 m BOAO telescope is operated more frequently than our SLODAR instrument, as its spectrometry does accept a partially cloudy sky for observations and because it is operated by on-site personnel.

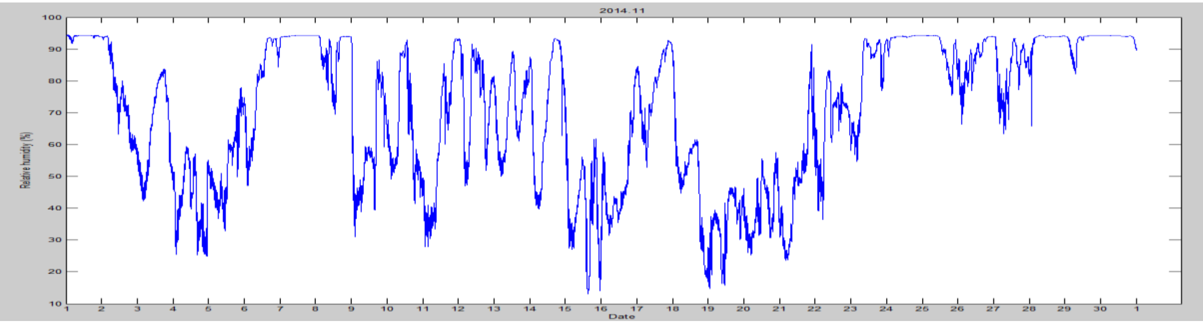


Figure 5. Humidity variations over one month (Nov. 2014)

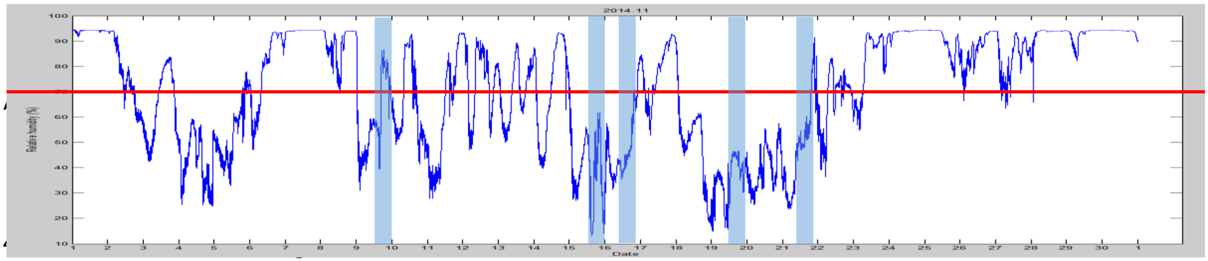
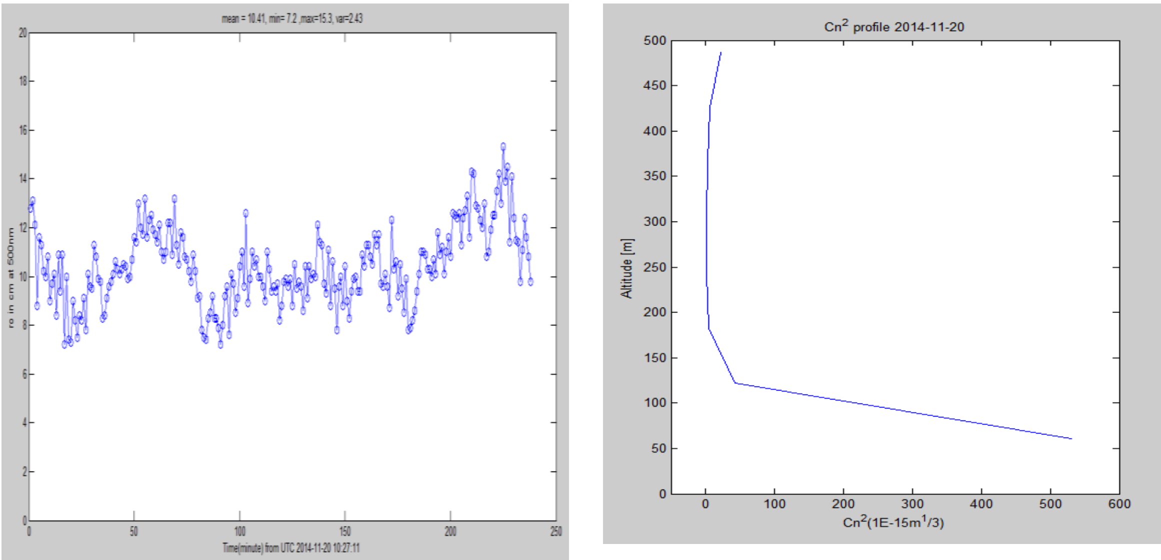


Figure 4. Humidity variations over one month (Nov. 2014), with clear and observable nights marked

Figure 6-a plots the total seeing at a wavelength of 500 nm over one night (20 Nov. 2014). The mean value was 10.41 cm with a standard deviation of 2.43 cm. Figure 6-b plots the C_n^2 vertical profile on the same day, showing that the ground layer below 60 m was dominant in the seeing profiles. Later, with more observations, the height of the ground layer was found to be less than 30 m. Figure 7 continuously plots the temporal variations of the total seeing over all observed nights. The overall seeing value is 8.28 cm, with a standard deviation of 2.25 cm. Over the observation times, no strong seasonal variations were experienced.



a) Temporal variation of the total seeing b) Mean C_n^2 vertical profile

Figure 6. Temporal variation of the total seeing values over one night (20 Nov. 2014) and the mean C_n^2 vertical profile

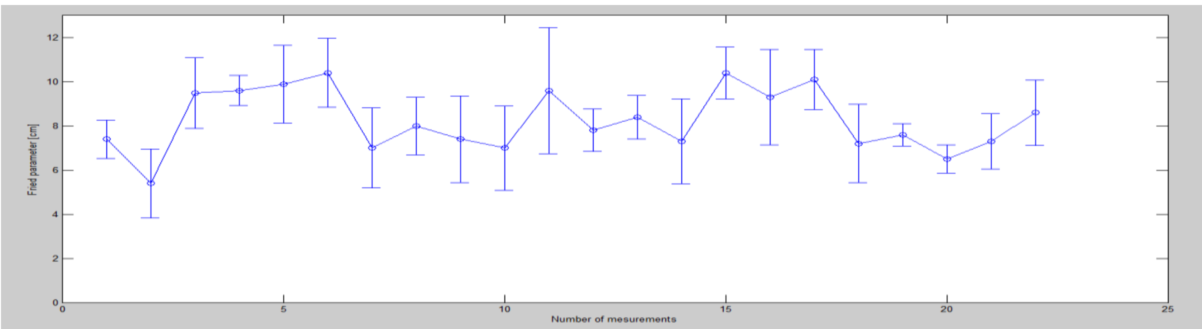


Figure 7. Temporal variation of the total seeing over one year (mean values with one sigma error bar)

5. DISCUSSION

We report the development of SLODAR for the characterization of the vertical profiles of atmospheric optical turbulence at the Bohyunsan Observatory in South Korea. We found that the environmental conditions at the site are becoming worse in terms of the number of observable nights but that the astronomical seeing itself is better than previously reported values, reaching 8.28 cm at 500 nm. Currently, an independent measurement instrument, in this case a DIMM instrument, is under consideration in the continuing effort to confirm SLODAR measurements.

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