Characterization of Optical Aberrations with Scanning Pentaprism for Large Collimators

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Abstract: We present a systematic study and practical implementation of characterizing optical aberrations of large collimators using scanning pentaprism technique and reconstructing the transmitted wavefront. Quantitative agreement between measurement results and theoretical predictions validates our methodology. © 2022 The Author(s)

1. Introduction
Telescopes launching large collimated or focused light with the aperture diameter greater than 20 cm have been widely used in diverse research fields including laser ranging satellites [5], laser guide stars [2], and free-space optical communications [1, 3]. Since their performance can be influenced by the optical aberrations, it is desirable to have the characterization of aberrations and precise measurement of divergence angles, especially in systems requiring tunable or specified focal conditions of launched beams. However, the required commercially available devices such as shearing interferometers, limit aperture sizes of test optics typically up to 10 cm.

We developed a mobile wavefront measurement system for large optics using a scanning pentaprism technique, which allows accurate slope measurements of the incident beam’s wavefront. By scanning a horizontal diameter of the test optic and analysing the slope of the detected centroids, one can obtain the divergence angle of the transmitted beam. To achieve the wavefront slope, \( S \), we consider \( f \) as the focal length of a plano-convex lens that focuses the beam on the detector. Then in case of a diverging/converging beam, the incident angle of light \( \theta \) is converted to the centroid displacement by \( \Delta = f \tan(\theta) \). Therefore, \( S \) which implies the ray variation relative to \( x \) axis, can be written as:

\[
S = \frac{\partial W(x,y)}{\partial x} = \tan(\theta) = \frac{\Delta}{f} \quad (1)
\]

A simple numerical integration of the measured slopes over the scanning range yields the reconstruction of the transmitted wavefront: \( S_i = W_{i+1} - W_i / h, \) where \( h \) is the spacing between the pentaprism positions. If \( N \) is the number of positions during the scanning, then the wavefront can be reconstructed using \( \vec{S} = A\vec{W} \), where \( A \) is a \( N \) by \( N + 1 \) sparse matrix.

2. Experimental Setup
Our wavefront sensor is based on a scanning pentaprism with a 4mm iris mounted on a motorized linear stage with straightness of 0.085 mm and travel range of 40 cm which is controlled by a stepper motor and is mounted on a height-adjustable heavy duty metrology stand to maintain the stability during the tests. The incident beam is generated by an external cavity diode laser with continuous-wave mode at 785 nm, coupled to a single mode fibre which is fixed on a 3-axis translation stage to facilitate alignment. The beam that is transmitted through the lens test goes to the pentaprism to be focused on a camera using a retroreflector and a plano-convex lens. Fig. 1 (a) shows the setup.

To estimate the measurement precision of centroid positions after accounting higher order effects, we investigated the variation of centroid positions as a function of the rotation angles of the pentaprism via three-dimensional raytracing. As a result, we obtained that the rotation around the \( x \)-axis (\( \alpha \) rotation) showed the most significant impact on the slope measurement, with quadratic response, while the centroid measurement was relatively insensitive to the rotation around \( y \) and \( z \) axes. Furthermore, we performed a Monte-Carlo analysis to determine the precision of the slope measurement. By varying the incident angle \( \theta \) from -50 \( \mu \)rad to 50 \( \mu \)rad with 11.1 \( \mu \)rad increments and sampling ten thousands randomly distributed pentaprism-rotation angles in a range from -0.25 rad to 0.25 rad at each incident angle, we gained the centroid position uncertainty of 2.5 \( \mu \)m, which corresponds to 5 \( \mu \)m divergence-angle uncertainty.
3. Results

To performed the test, we discretized the measurement range of the scanning pentaprism with step size of 2 mm. At each position, the camera adjusted its exposure time to keep a good signal-to-noise ratio (SNR > 10) while ensuring no saturated pixels. Then, we captured twenty frames of images and calculated the centroid positions in the x-direction for all images. The full scan of the pentaprism was repeated five times and took about 30 minutes.

We measured the centroid displacement at various positions of the launch fiber to characterize and calibrate our measurement apparatus. First, we measured the test optic focal length by shifting the launch fiber in the z-direction by ±2.54 mm and removed the test optic’s surface irregularity effect to compare the divergence or convergence of the beam, owing to the de-focused fiber position, to a three-dimensional raytracing model. By characterizing the closeness between the theory and experiment, we achieved 99.8% in both −2.54 mm and +2.54 mm fiber shifts (Fig. 1 (c) and (d)). Moreover, we reconstructed the transmitted wavefront from the measured centroid positions shown in Fig. 1 (c). The wavefront is normalized by the wavelength of $\lambda = 785$ nm, as plotted in Fig. 1(e). The averaged uncertainty over the 20 cm travel range of the pentaprism was estimated to be $\delta W = 0.007\lambda$. This exceptional precision is comparable with the performance of shearing interferometers [4]. Finally, we characterized the aberrations for a tilted optic and compared the measurement with our raytracing model (Fig. 1(f)). The results indicate 99.9% and 99.6% closeness for the $-1.5^\circ$ and $+1.5^\circ$ tilt angles, respectively.

4. Conclusion

We developed a practical characterization system for optical aberrations of laser launching telescopes. We performed a proof-of-principle experiment for a linear measurement of the transmitted wavefront and analyzed the measurement apparatus using a three-dimensional raytracing method. With sufficiently redundant measurements and statistical analysis, it was shown that our wavefront-measurement system exhibits the precision better than 0.01 $\lambda$. Our scheme can be readily extended to two-dimensional measurement of wavefronts and can be implemented at reasonable costs to be used for both scientific and industrial applications in diverse fields including optical satellite communications and astronomical observatories.

References

1. Hemani Kaushal, V. K. Jain, and Subrat Kar. *FSO System Modules and Design Issues*. Springer India, 2017.
2. Ronald R. Parenti and Richard J. Sasiela. Laser-guide-star systems for astronomical applications. *J. Opt. Soc. Am. A*, 1994.
3. R. Ursin and et al. Tiefenbacher. Entanglement-based quantum communication over 144 km. *Nature Physics*, 2007.
4. Byron M. Welsh, Brent L. Ellerbroek, Michael C. Roggemann, and Timothy L. Pennington. Fundamental performance comparison of a hartmann and a shearing interferometer wave-front sensor. *Appl. Opt.*, 1995.
5. Matthew Wilkinson and et al. Schreiber. The next generation of satellite laser ranging systems. *Journal of Geodesy*, 2019.