Optical measurement of materials and lens assemblies at specific or varied temperatures

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Abstract

Optical materials and lens assemblies are specified for use at various operating temperatures. Ophthalmic lenses such as intra-ocular (IOLs), rigid gas permeable (RGP), and soft contact lenses must be verified at a single well-controlled temperature to ensure correct performance. In comparison, lens assemblies for UAVs (unmanned aerial vehicles) and other "outdoor" applications demand performance over a substantial range of temperatures. Both applications demand the ability to integrate temperature monitoring or control with optical measuring instruments. A common practice is to thermally soak the material or lens assembly and then attempt measurement before the object under evaluation returns to ambient room temperature. We are reporting on the utilization of a NIST-traceable temperature device combined with wavefront sensing technology for faster integrated measurement capability. The temperature sensor is currently capable of 0.01 and 0.1 degree C resolution and accuracy; respectively for an operating range of 0 to 100 degrees C. Efforts are underway to extend the temperature measurement range down to -30 C. The wavefront measurement device is a Shack-Hartmann sensor (SHS) operating at 5 to 15 Hz with simultaneous gauging of temperature. The SHS can be operated with a choice of wavelengths from 400 to 1,000 nm. It also supports both single and double-pass configurations. The single-pass arrangement was chosen for these experiments due to the simpler, more compact set-up. The dynamic range of the wavefront sensor is first utilized to evaluate the temperature chamber. Results are then presented for two lens assemblies intended for commercial UAVs.

Keywords
astronomy, ophthalmology, interferometry, laser testing, optical alignment, Shack-Hartmann sensor, and lens testing

Development of the Shack-Hartmann sensor

The development and early application of the SHS is well documented[1] in a paper authored by Dr. Roland Shack and Dr. Ben Platt. Applications include atmospheric correction for ground-based astronomy, corneal profiling, retinal imaging, laser testing, optical alignment and commercial optics testing. In this paper, we seek to utilize the technology for evaluating assembled lenses over a range of operating temperatures.

Temperature "chamber" considerations

For testing "photographic" quality infinity corrected objectives, a single-pass configuration was preferred for simplicity and compactness. The lens under test would be illuminated with a high quality spherical wavefront over-filling the aperture of the objective. The wavefront transmitted by the lens under test would then pass to the wavefront sensor.

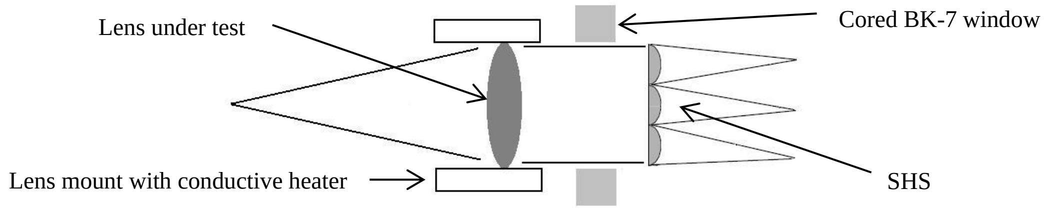


Figure 1. Thermal chamber layout (single-pass null)

The lens under test was subjected to a range of temperatures by means of thermal conduction via the aluminum lens mount. The temperature sensor was affixed to this lens mount. Aluminum was chosen for its high thermal conductivity. The lens mount sat atop a borosilicate (BK-7) window with cored out center to allow the wavefront to pass unimpeded. In turn, the BK-7 window sat directly atop the mounting flange of a small SHS. The thermal conductivity of aluminum, glass and air at room temperature are approximately 200, 1 and 0.02 watts per meter kelvin; respectively. While other materials with lower thermal conductivity may have been used to couple the lens mount and SHS, glass was preferred for exacting control of flatness and parallelism.

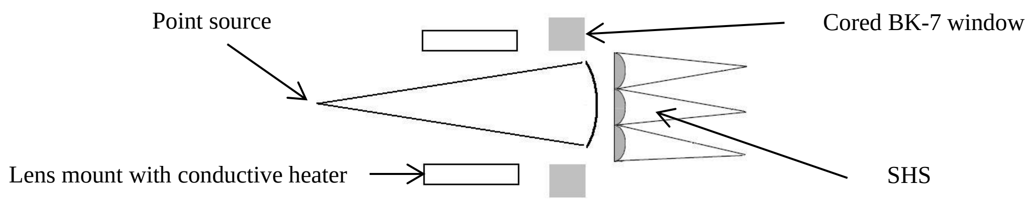


Figure 2. Thermal chamber layout (single-pass non-null)

Evaluation of thermal chamber

Utilizing a single-pass non-null configuration, the spherical wavefront divergent from a point source at 632.8 nm was detected by the SHS. The raw wavefront was approximately 18 waves peak to valley (PV), as the distance between the point source and microlens plane of the SHS was ~197 mm. Upon activation of the heater, we collected ~2,000 sets of single camera frame wavefront data over ~200 seconds (10 Hz data rate). The ~150 mm long aluminum lens mount increased in length by ~0.5 mm during this period as its temperature increased 120 C (20 C to 140 C). The SHS provided stable wavefront results during the fast thermal excursion; reported values are after removal of tilt and defocus.

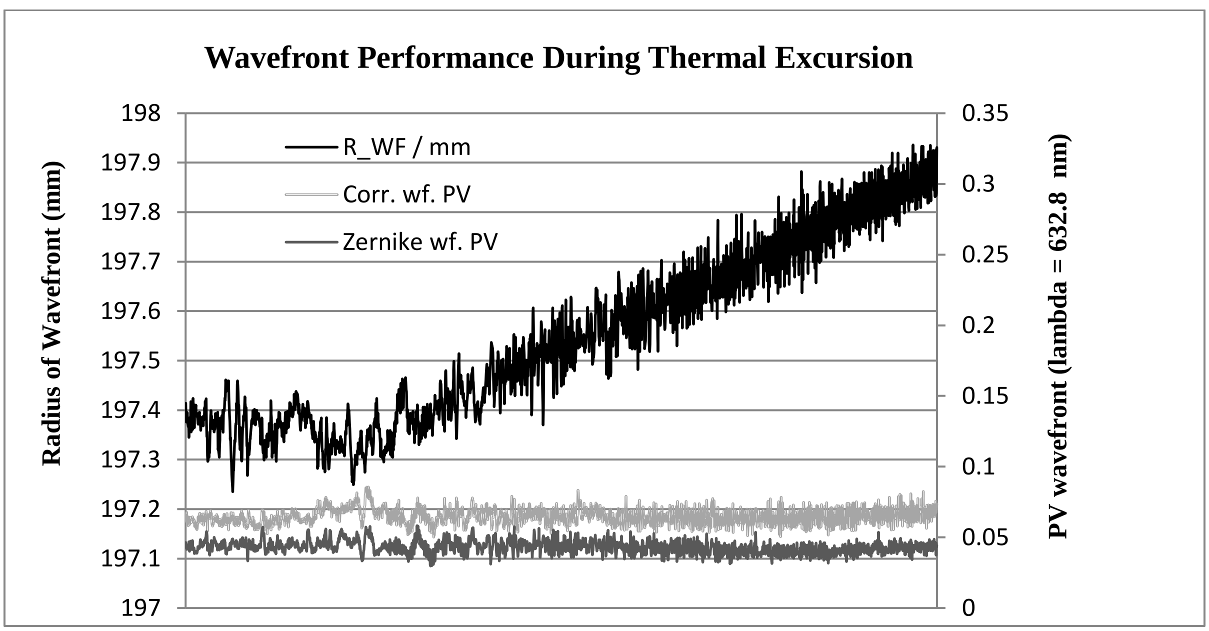


Figure 3. Wavefront curvature (mm) and PV wavefront measurement over ~120 C lens mount heating

Wavefront measurement accuracy

The SHS utilized for these experiments featured a 4.8 mm by 6.4 mm active aperture with 150 micron microlens pitch. This SHS has a basic wavefront accuracy of ≤ 50 nanometer PV (~λ/12 PV for λ= 632.8 nm). We under-filled the active aperture of the SHS to allow for substantial drift and defocus of the wavefront to be measured.

Wavefront measurement was performed before and after the fast thermal excursion to evaluate the SHS performance of the proposed configuration. PV and rms wavefront were 0.072/0.012 waves and 0.071/0.010 waves; respectively for 20 and 140 C, indiscernible from the basic accuracy of the SHS.

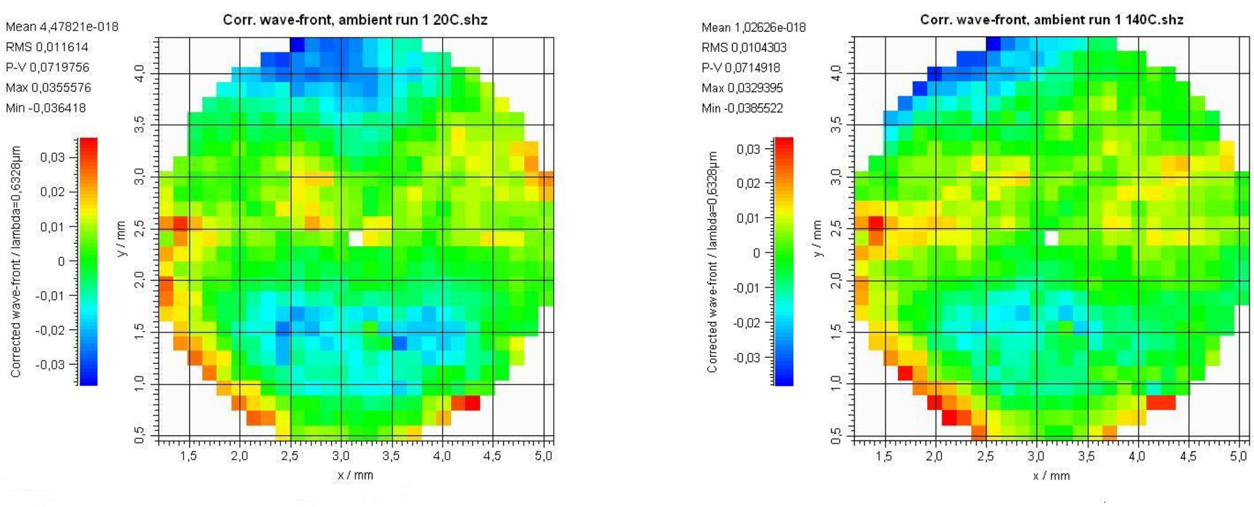


Figure 4. Corrected wavefront of point source at 20 C (top) and 140 C (bottom)

Satisfied with the short term performance, we evaluated the SHS wavefront results for extended periods of time (hours) at several discrete temperatures ranging from 20 C to 100 C. We observed the wavefront error for the non-null configuration increased to 0.11 ~ 0.13 waves PV. Checking the SHS, we determined that a significant temperature rise above ambient room temperature had occurred, presumably due to prolonged thermal conduction between the cored window and the SHS assembly. The addition of three (3) small precision borosilicate spheres between the cored window and the SHS along with a larger aluminum mounting flange provided sufficient passive temperature control to return wavefront performance to a desirable level.

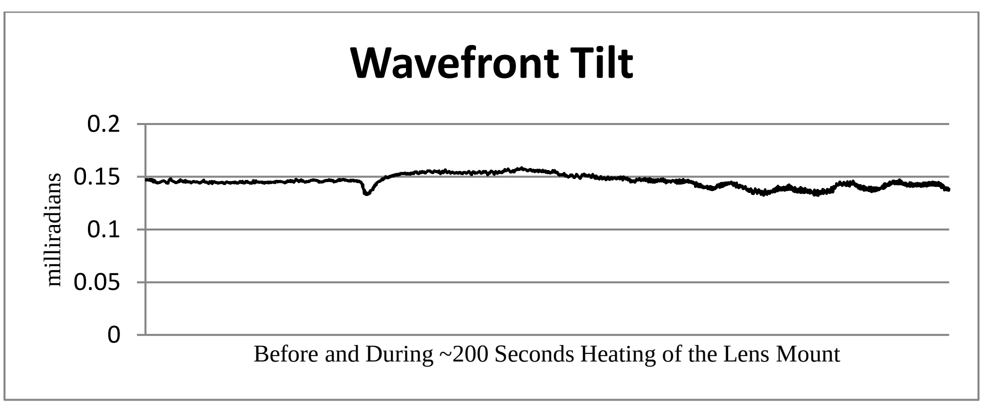
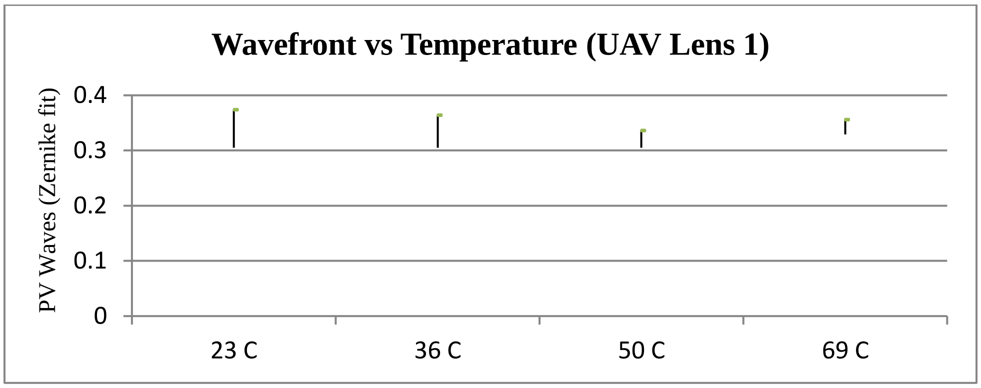


Figure 5. Wavefront tilt (mrad) before and during ~120 C temperature rise of lens mount

Part of the appeal of direct coupling of the SHS to the thermal test set-up is the possibility of measuring wavefront tilt, or more precisely changes in wavefront tilt. Unlike traditional interferometry, the SHS does not require a reference and as such may be used to measure boresight error and or lens distortion in a fast, convenient manner. During the fast thermal excursion (120 C over 200 seconds), the change in wavefront tilt +/- 2 standard deviations was < 0.03 milliradians.

UAV Lens Results

The first lens evaluated was a f/2.5 infinity corrected objective designed for the near-infrared (NIR) and short-wave infrared (SWIR) spectral regions. It is a fixed focused lens with aluminum lens housing. Bar plots report PV wavefront error for ISO 36 term Zernike fit with +/- 2 standard deviations for ~150 measurements at each reported temperature.



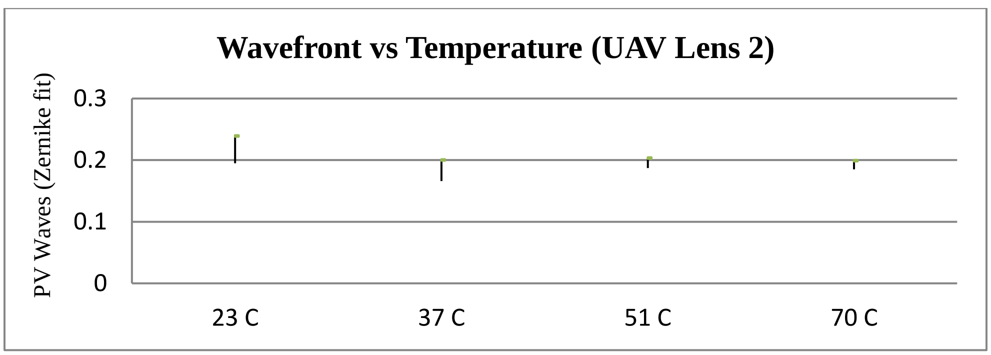


Figure 6. Wavefront error of UAV lens 1(top) and lens 2 (bottom) tested at several discrete temperatures

The second lens evaluated was a 5X zoom lens designed for visible wavelengths. It was evaluated at a middle focal length setting and corresponding f/5 aperture. This lens construction features injection molded mechanical components.

Wavefront Accuracy

In an earlier study[2], other groups have compared wavefront measurement results for double-pass SHS with double-pass phase measuring interferometry. In that experiment, relay optics were utilized to image the pupil of the lens under test to their respective sensors. Seeking a simpler, more compact test set-up, we elected to forgo the more rigorous implementation of pupil imaging optics for the SHS configuration. Additionally, our set-up had a high quality f/2 objective to illuminate the lenses under test, and was considered negligible in terms of error contribution. To assess both of these aspects, we measured UAV lens 1 at ambient room temperature with a Twyman-Green phase shifting interferometer as well as with our single-pass SHS set-up. The results are included below. The C8 and C15 Zernike terms represent primary (spherical aberration) and the next higher order rotationally symmetric aberration.

Double pass phase shift interferometry	Singlepass Shack-Hartmann sensing
0.376 waves PV	0.343 waves PV
0.081 waves rms	0.082 waves rms
C8 = +0.017 waves	C8 = +0.016 waves
C15 = -0.020 waves	C15 = -0.016 waves

Table 1: Comparing double-pass interferometry and single-pass Shack-Hartmann measurement for UAV lens 1.

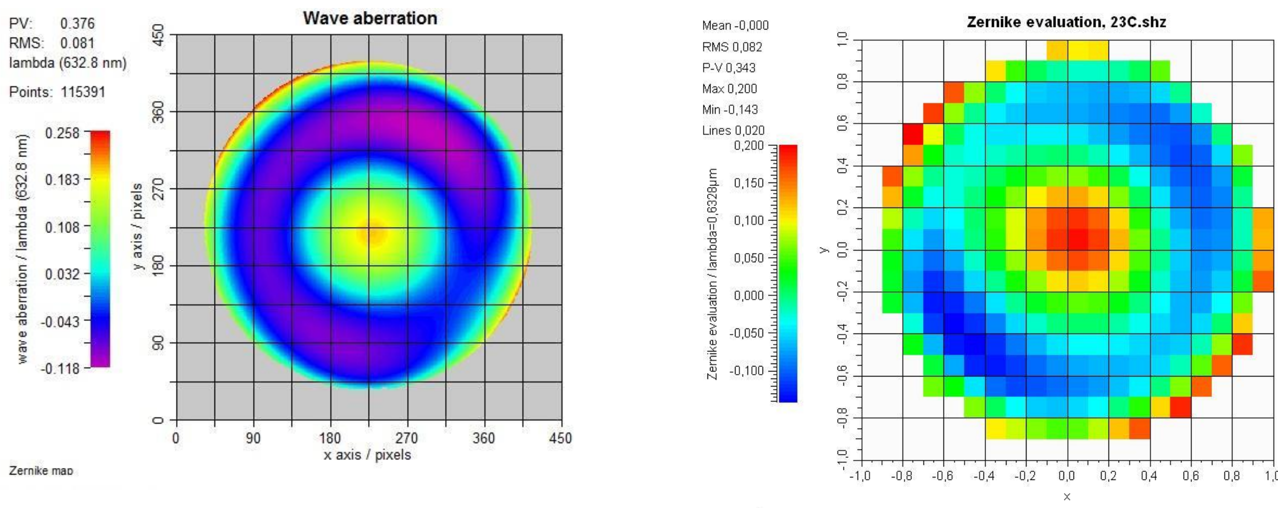


Figure 7: Comparing double-pass interferometry and single-pass Shack-Hartmann measurement for UAV lens 1.

Conclusions

The SHS provided a simple and accurate means for testing lens wavefront performance over a significant range of temperatures. The elimination of pupil relay optics did not have a material effect on the measurement accuracy for the two diffraction limited lens assemblies evaluated. It remains to be seen whether the simple thermal chamber approach can be successfully implemented at substantially lower operating temperatures (-30 C), particularly with regard to the challenge of condensation.

Acknowledgements

The author would like to express his gratitude to Uli Berg of Optocraft GmbH for his many thoughtful and helpful discussions in preparation of this paper.

References

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2. Pfund, J., Lindlein, N., Schwider, J., Burow, R., Bluemel, T., Elssner, K. E.,”Absolute sphericity measurement: a comparative study of the use of interferometry and a Shack-Hartmann sensor,” Optics Letters, Vol. 23, No. 10, May 15, 1998.