A Practical Implementation of the Random Ball Test
Robert E. Parks

The random ball test for calibrating interferometer transmission spheres[1] was reported about 8 years ago but there did not appear to be an ideal ball. Now, nearly ideal balls are available.

Although the idea must have been around for years the use of a ball for the calibration of interferometer transmissions spheres was, to our knowledge first reported in 1999. The ball used at the time was made of black (neutral density filter) glass and worked fine for a demonstration of the principle but was not really practical because of its relative softness of the glass and susceptibility to damage in everyday use.

Other ball artifacts were tried without great success. High grade chrome steel balls are quite round but are easily dented and have a high reflectivity that is not a good match for an uncoated transmission sphere. The chrome steel also has an affinity for fingerprints and tends to corrode due to them just enough to roughen the surface. Zerodur or other transparent glass balls do not work because of a reflection off the concave surface as well as the convex. This problem can be solved by drilling half way through the ball but this leaves a defect in the surface. Most forms of ceramic balls have a poor surface finish because they are made by a sintering process that does not yield fine grain sizes. Silicon balls are another possibility but the regular crystal structure of the material makes it difficult to make truly round balls.

Relatively recently we found silicon nitride balls[2] that overcome these objections. Balls in 25 mm sizes are Grade 5, meaning round to better than 5 microinches (125 nm), have a surface finish of about 1.3 nm rms, are opaque, have a reflectivity of about 11% in the visible and are virtually indestructible. These qualities make the silicon nitride balls a practical answer to a test artifact that can be used repeatedly in a calibration situation for years without fear of degradation.

At this point it pays to review the random ball test. A ball of about 25 mm in diameter is located so that its center is precisely at the transmission sphere focus as shown in Fig. 1. The ball should be centered well enough that no more than one fringe is seen in the aperture. An interferogram is taken and the wavefront data stored after removing tip, tilt and focus. The ball is picked up, rotated so that an arbitrary new patch of the surface is viewed by the transmission sphere, carefully re-centered and another interferogram taken. When a series of interferograms have been taken they are averaged and the average is a close approximation of the residual errors in the transmission sphere.

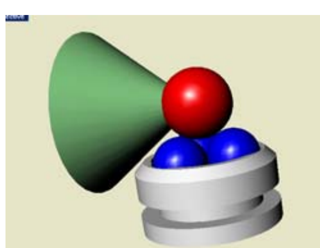

Fig. 1 Calibration ball sitting on a three point kinematic mount with the green cone representing the light from the transmission sphere focused at the center of the ball. The ball acts like a convex mirror and directs the light back into the interferometer over the same path that it exited.

To show that the average of the interferograms of the ball represent a statistical approximation of the errors in the transmission sphere we follow the logic of Creath and Wyant[3] in a paper on calibrating surface finish measuring interferometers. They argue that if a smooth plane mirror is sampled in non-overlapping regions the topography of those regions is uncorrelated and independent. Therefore the measured rms error is the root sum square of the rms of the mirror plus the rms of the Mirau objective and reference mirror in the objective used to make the measurement. Similarly we argue that the rms of the interferogram of the calibration ball is the root sum square of the rms of the errors in the ball plus the rms errors in the transmission sphere because different patches of the ball are uncorrelated and independent.

In other words,

$$\sigma_{\mathrm{int}erferogram} = \sqrt{\sigma_{ball}^2 + \sigma_{TS}^2}$$

where $\sigma_{\mathrm{int}erferogram}$ is the rms of any one interferogram, σ_{ball} is the rms of the patch of the ball being measured and σ_{TS} is the rms error in the transmission sphere.

The rms error in the knowledge of the wavefront error of the transmission sphere found using the random ball test is the rms error in the patches of the ball divided by the square root of the number of interferograms averaged, Creath and Wyant eq. (11), or

$$\sigma_{error} = \frac{\sigma_{ball}}{\sqrt{N}}.$$

Finally, to find the rms error in the ball patches being measured, again following their logic, we can difference any two interferograms to give σ_{diff}. Since the statistics of any two ball patches is the same the rms error of the patches should be the same. Therefore,

$$\sigma_{ball} = \frac{\sigma_{diff}}{\sqrt{2}}.$$

Results of some typical measurements using an f/3.3 transmission sphere showed the rms difference between two measurements to be about 4.4 nm which means the rms figure of the ball over the patch viewed to be about 3.1 nm rms. Then the question becomes how many interferograms should be averaged to reduce the error in knowing the wavefront of the transmission sphere? In a paper by Ulf Griesmann[4] he suggests that the error be less than the repeatability of the measurement where the ball is not moved.

We found that during our test the repeatability was about 1.65 nm rms. This suggests that the error in knowing the transmission sphere wavefront is reduced to less than the repeatability of the test when four or more interferograms are averaged in our test environment using an f/3.3 diverger. Clearly the result will be different for every set of test conditions. On the other hand, this analysis offers a straightforward method of establishing the errors associated with performing the random ball calibration. It also shows that ultimately the calibration is independent of the figure of the ball, it just takes far fewer interferograms in the average if the figure and finish of the ball are good.

To illustrate these results Fig. 2 shows the four wavefront maps of individual tests with tip, tilt and power removed along with the p-v and rms of each. Fig. 3 then shows the difference between the first two measurements in Fig. 3 to show a typical difference map and why the rms error in the ball is on the order of 3 nm. Fig. 4 is the average of the four interferograms in Fig. 2. Clearly the coherent error, that is, the result of the average is far greatly than any error in the ball.

In conclusion we have shown that the random ball test is an easy to do calibration of transmission spheres that is independent of the quality of the ball but that a ball with good figure and finish makes the test quick to do. Further, the results of the test are difficult to argue with. There is one caveat; the test is susceptible to retrace errors if the f/number of the transmission sphere is too slow. Caution is advised for transmission spheres f/8 and slower.

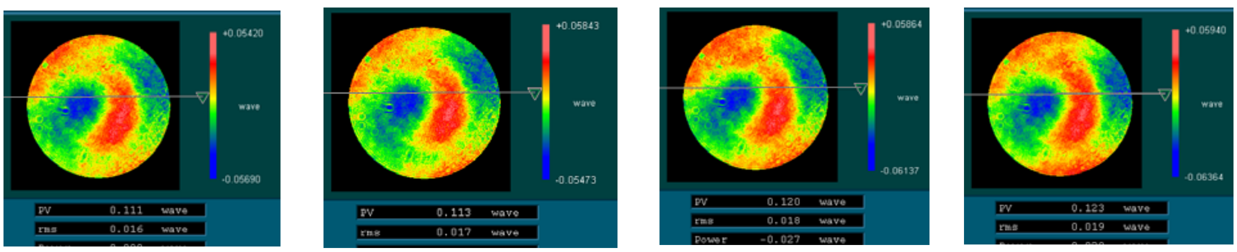

Fig. 2 Contour maps of the test of the random ball in four different test patches
P-V ranges from .111 to .123 λ and rms from .016 to .019 λ

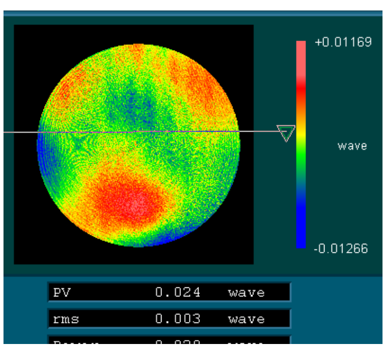

Fig.3 The difference between the first two contour maps in Fig. 2

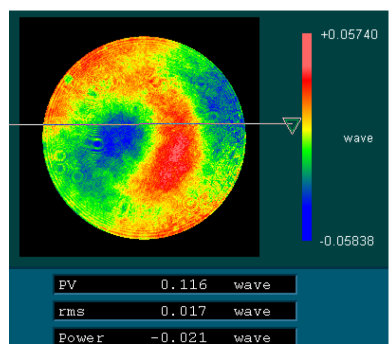

Fig. 4 The average of the four contour maps in Fig. 2, that is, the error in the f/3.3 transmission sphere

[1]R. E. Parks, C. J. Evans and L. Shao, "Calibration of interferometer transmission spheres", in *Optical Fabrication and Testing Workshop OSA Technical Digest Series* **12**, pp.80-83, 1998
[2]http://www.cerbec.com/main/home.asp
[3]K. Creath and J. C. Wyant, "Absolute measurement of surface roughness", **Appl. Optics, 29**, 3823-7 (1990)
[4]U. Griesmann, Q. Wang, J. Soons and R. Carakos, " A Simple Ball Averager for Reference Sphere Calibration", **Proc. SPIE, 5869**, 189-96 (2005)

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