Tolerancing, Specifying and Measuring Spherical Radius

Rick Plympton
Optimax Systems, 6367 Dean Parkway, Ontario, NY USA

This paper will review tolerancing schemes for spherical radii, including the historical origins. It finishes with recommendations for specifying tolerances for spherical radii.

POWER TOLERANCE VERSUS RADIUS TOLERANCE

There are two main paths for tolerancing spherical radii: power tolerance and linear radius tolerance. Both measure change relative to a nominal value, but the metrology used is the key difference.

Power Tolerance: Controls radius through increments of sag change relative to a test plate of known radius. The sag difference between the known radius and the surface under test is measured, from which the radius of the surface can be calculated.

Linear Radius Tolerance: Controls radius in linear units relative to the nominal. Radius is measured directly using an interferometer equipped with distance measurement capability.

Either path controls variance in radius and is sufficient on its own.

Traditional Method - Test Plate

Before lasers, the workhorse tool for form measurement of spherical and flat optical surfaces was the test plate[1]. Bringing the test plate and the surface under test into close contact formed interference fringes known as Newton Rings. While spherometers could be used in radius measurement a test plate based measurement was more useful. The quantity and nature of these rings indicated the form accuracy of the surface under test relative to the test plate. Radius and irregularity (deviation from perfectly spherical) were qualitatively measured using the test plate, and what was seen using a test plate was a combined power and irregularity[2]. Radius error was determined as round interference fringes of spherical power, and the number of fringes permitted was known as power.

With test plate based metrology the traditional method chose power in proportion to allowable irregularity. Since test plating was the only available option for measuring radius and irregularity, and since power masks irregularity[3], tolerancing power with respect to irregularity was necessary. Keeping power smaller did not lead to a smaller irregularity, but it did enhance the optician's ability to evaluate irregularity. To guarantee irregularity detection the power tolerance (~4x specified irregularity[4]) may have been kept smaller than required for the desired optical performance.

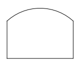
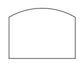
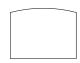
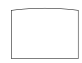
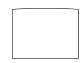
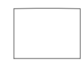
Current Methods – Interferometric Testing

With interferometry, power is separate from irregularity, and the traditional power-irregularity relationships need not be kept[5]. Interferometers are found in most shops, often located directly in the manufacturing area. Test benches with synchronized wavefront mapping and distance measuring interferometers (DMIs) provide independent measurements of irregularity and radius[6]. In addition, modern optical design software makes modeling each tolerance's contribution possible. Where test plate-based tolerancing would require a power tolerance of 2 to 3 fringes to detect a ½ fringe irregularity tolerance, with interferometry radius could be specified to the limits a tolerance analysis shows independent of allowable irregularity.

RADIUS TOLERANCING RECOMMENDATIONS

A power tolerance or a linear radius tolerance is sufficient on its own, and choosing one over the other is driven by metrology to be used. With interferometry as the metrology tool, radius can be toleranced independent of irregularity, but when test plating radius needs to be toleranced in proportion to irregularity.

Power tolerances can become very challenging specifications for the optician as the f/# (radius/aperture) of the surface gets smaller. For example, meeting a 3 fringe power tolerance on an f/7 surface is much easier than 3 fringes on an f/0.7 surface. The table below summarizes this phenomenon.

	Radius Deviation (mm) as a Function of f/# and Power					
						
Power at HeNe $\lambda = 0.6328\mu m$	f/0.75	f/1	f/2	f/4	f/8	f/16
1 Fringe	0.0009	0.0020	0.0096	0.0400	0.1615	0.6475
3 Fringe	0.0028	0.0061	0.0289	0.1201	0.4846	1.9425
5 Fringe	0.0046	0.0102	0.0482	0.2001	0.8076	3.2376

OPTICIAN'S PERSPECTIVE: GENERAL MANUFACTURING TOLERANCES

Commercial Tolerance
Radius tolerance ±0.2% **OR** ±5 fringes power from a test plate, whichever is equivalently larger[7]

Precision Tolerance
Radius tolerance ±0.1% **OR** ±3 fringes power from a test plate, whichever is equivalently larger[4]

Manufacturing Limit
Radius tolerance ±0.0025mm **OR** ±1 fringe power from a test plate, whichever is equivalently larger[4]

RADIUS TOLERANCING SUMMARY

- **Radius can be toleranced using fringes of power OR stated as a linear radius tolerance**
  - In the end specifying only one is sufficient, and one can be converted into the other
  - If both are specified an explanation must be provided by the customer or sought by the manufacturer
  - Power is still useful when tolerancing plano surfaces because a radius tolerance there is meaningless

- **Radius tolerancing has traditionally stemmed from the metrology to be used**
  - Interferometry has broken the connection between power and irregularity[3], and the modeled radius tolerance may be applied in full independent of irregularity specified.

- **Know the metrology to be used and match the tolerancing scheme to it**
  - If metrology to be used is test plating, fit the design to the manufacturer's test plates and reoptimize. Fringes of power relative to the fitted test plate radii would be the units of choice for tolerance here.
  - For interferometric radius measurement, update the design model with actual measured radii and reoptimize lens spacing. Linear units of radius relative to the nominal radius would be the units of choice for tolerance here.

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[1] H.H. Karow, *Fabrication methods for precision optics*, Ch 6.1, John Wiley & Sons, New York City, 1993
[2] Ibid, Pg 642
[3] W.J. Smith, *Modern Lens Design*, Pg 574, McGraw Hill, New York City, 2005
[4] H.H. Karow, *Fabrication methods for precision optics*, Pg 641, John Wiley & Sons, New York City, 1993

[5] R.E. Fischer, B. Tadic-Galeb, P. Yoder, *Optical System Design*, Pg 495, McGraw Hill, New York City, 2008

[6] H.H. Karow, *Fabrication methods for precision optics*, Pg 650, John Wiley & Sons, New York City, 1993

[7] The radius tolerance will come up first for small f/# lenses (< f/1) and the power tolerance is the restriction for higher f/# lenses (> f/10).