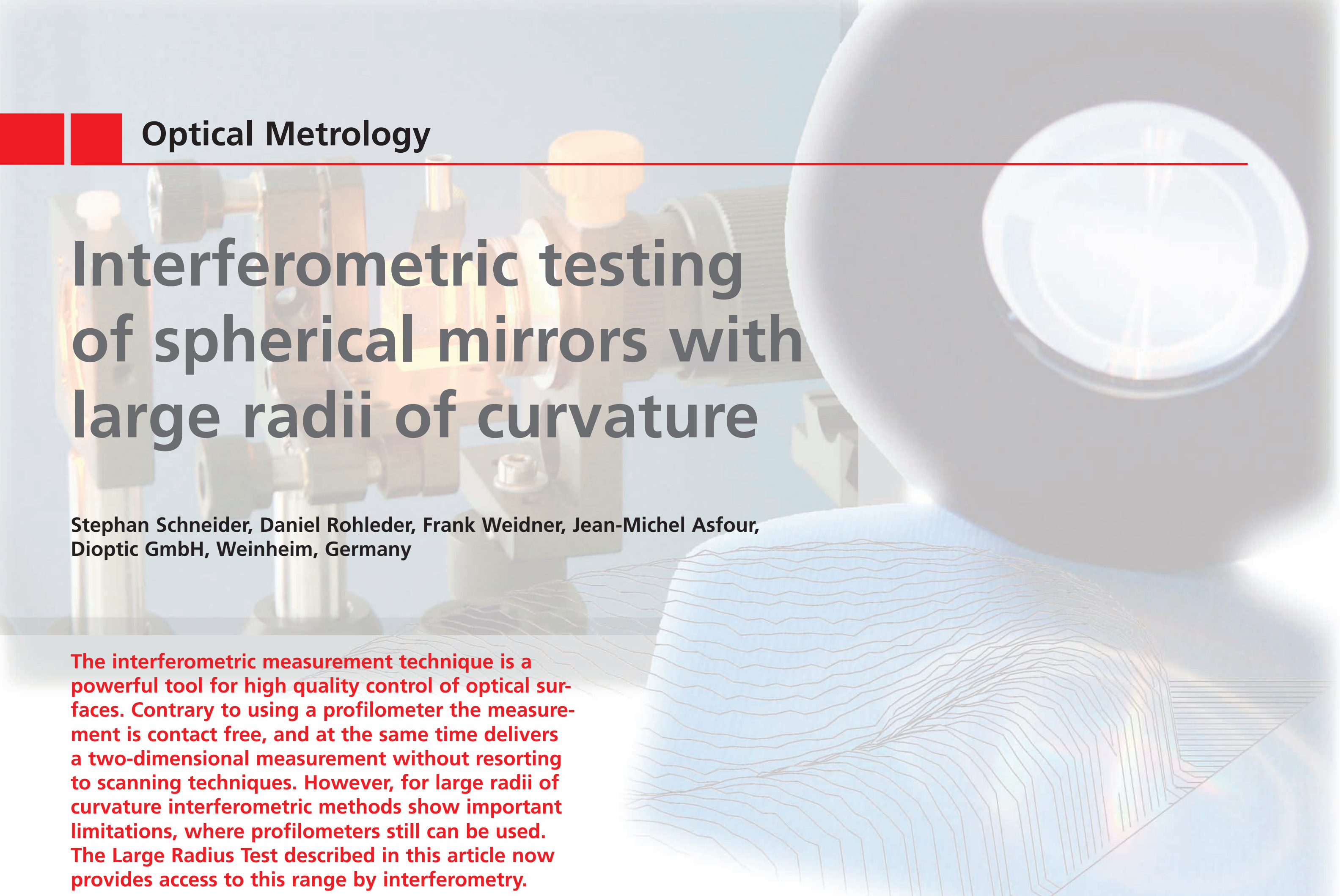

Interferometric testing of spherical mirrors with large radii of curvature

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The interferometric measurement technique is a powerful tool for high quality control of optical surfaces. Contrary to using a profilometer the measurement is contact free, and at the same time delivers a two-dimensional measurement without resorting to scanning techniques. However, for large radii of curvature interferometric methods show important limitations, where profilometers still can be used. The Large Radius Test described in this article now provides access to this range by interferometry.

Interferometric test of radius of curvature

Interferometers based on the Fizeau-Principle [1] are common tools for testing radii of curvature. A plane wave (**figure 1**, red arrows) is split into a reflected reference wave (blue arrows) and a transmitted object wave. Ideally, the object wave is reflected back undisturbed from the specimen. In this case the superposition of the reflected undisturbed object wave with the reference wave leads to a constant phase or to a so called interferometric null-test.

A typical setup for testing a concave mirror with a radius of curvature R is shown schematically in figure 1. First the mirror under test is placed in the "cat's eye" position, which is at the focal distance *f* of the measurement objective. Afterwards the specimen is moved along the optical axis up to the position where its radius of curvature fits precisely the generated object wave. The moved distance *Z* corresponds to the radius of curvature of the mirror under test. Surface irregularities are visible in the interferogram as phase changes. By varying the focal ratio *f/D*, with *D* denoting the beam diameter of the incoming wave, the measurement range of the radii of curvature can be adjusted continuously. The working distance *L*, which can be written as *L* = *f* + *R* for concave surfaces, is already far above useable dimensions of a standard laboratory for radii of curvature *R* > 2 m.

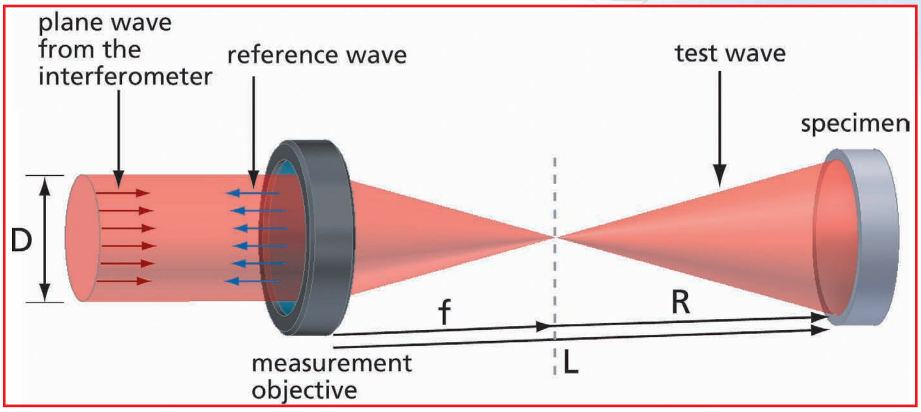


***Figure 1**: Setup for testing concave spherical mirrors. Beam diameter D, radius of curvature of specimen R, distance specimen to transmission sphere L*

In order to expand the accessible range of measurements using typical laboratory interferometer systems, one can use measurement objectives generating divergent object waves (**figure 2a**). These objectives are however not ideal, as the aforementioned cat's eye position is no longer present, and additionally, these objectives are only available in discrete steps with e.g. R = 3 m, 4 m, 8 m. Therefore, a test specimen with a radius of curvature R = 12 m using a diverging objective with a focal length f = -8 m still requires an optical bench with *L* = 4 m length. The Large Radius Test described here has the advantage to access a continuous measurement range of |*R*| ≥ 1 m using an interferometric setup with a length *L* = 0,8 m.

Enlarged range of measurement

Two components are necessary to enlarge the range of measurement – a Diffractive Fizeau Null Lens (DFNL) [2] and an achromat, the latter being movable along the optical axis (**figure 2b-d**). The DFNL generates a divergent wave and substitutes directly for the transmission sphere. By varying the distance between the DFNL and the achromat, the radius of curvature of the object wave can be adjusted continuously over a wide range. Making use of integrated alignment holograms, reference positions for the achromat can be easily found. These holograms generate

Originally published in German in Photonik 2/2007

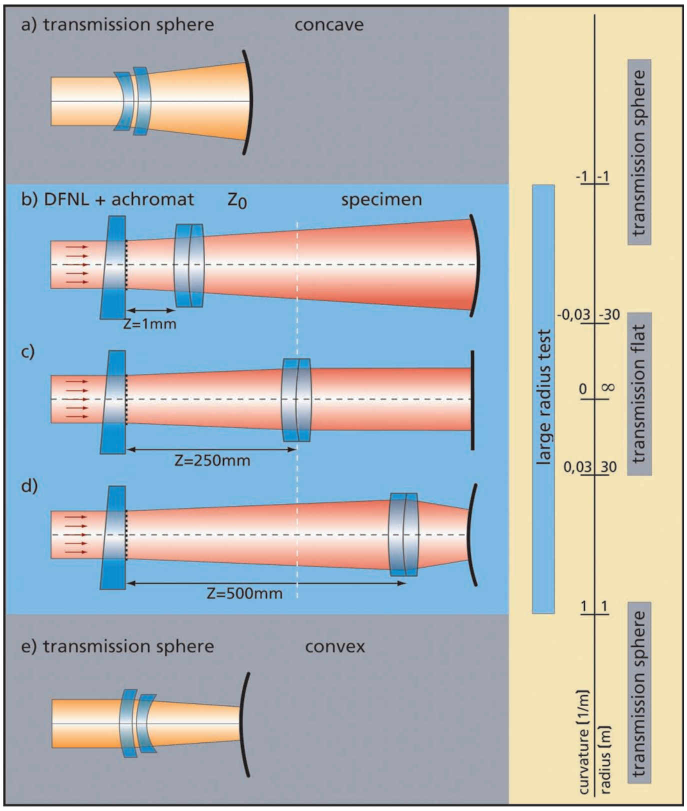
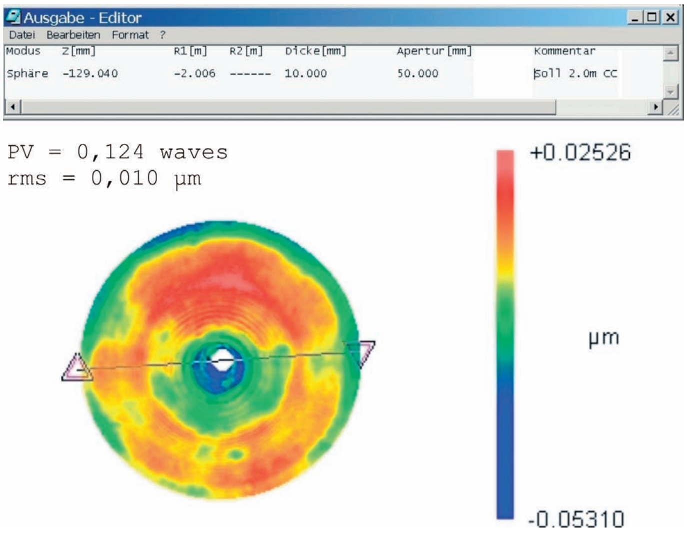


Figure 2: *Usually an interferometric radius test covers a measurement range with |R| < 1,5 m (gray bars). Using the Large Radius Test the range can be extended to |R| < ∞ (blue bar)*



Modus	Z[mm]	R1[m]	R2[m]	Dicke[mm]	Apertur[mm]	Kommentar
Sphäre	-129.040	-2.006	------	10.000	50.000	Soll 2.0m CC

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PV = 0,124 waves
rms = 0,010 µm
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Figure 3: *Top: Screen shot showing the results of the Large Radius Test. The mirror under test has a concave shape, a radius of curvature of R = 2 m and a diameter of D = 50 mm. The matched object wave is generated by placing the achromat at a distance of Z = -129,040 mm relative to the DFNL. Bottom: Interferometrically measured surface aberrations of the specimen relative to the reference wave*

focal points at predefined positions and thus permit alignment and adjustment similar to that utilising the cat's eye position described above.

Figure 2 compares the range of measurement of transmission spheres with the Large Radius Test. Transmission spheres usually cover the range of |*R*| < 1,5 m (figure 2a, e). Using a transmission flat, radii of curvature of |*R*| > 30 m are accessible by analysing the spherical deviation of the specimen from the plane wave. This evaluation of the spherical power of the fringes can be done by most of the available interferometer software. However, it is not an interferometric null test and requires the precise diameter of the specimen and additional numerical processing.

In contrast, the Large Radius Test always allows generation of a matched object wave, and provides for a null test spanning the whole range of radii with |*R*| > 1 m. Moving the achromat close to the DFNL (figure 2b) generates a divergent test wave, which can be used for testing concave specimens with radii of curvatures, e.g. *R* = -1 m. Moving the achromat further away from the DFNL generates a convergent test wave (figure 2d), permitting measurement of convex specimens with e.g. *R* = +1 m. At a distinct "Z_0-position", the object wave is exactly plane, which means a radius of curvature *R* = ∞. Object waves with continuous radii of curvatures can thus be generated. For any given test optic, the achromat is first placed at roughly the appropriate position on the z-axis, and from there is then fine tuned in order to minimise the residual spherical aberration.

The corresponding radius of curvature can be calculated from the Z-Position with a precision of measurement uncertainty of ΔR/R < 0,2% in the range |R| < 10 m and ΔR/R < 0.6% for |R| < 50 m (**figure 3** top). The interferogram additionally shows the deviation of the specimen from an ideal sphere (figure 3 bottom).

Correction of spherical aberrations

The Large Radius Test is not a strict Fizeau setup, as the test is performed on the combination of the achromat and specimen together inside the Fizeau cavity. Thus, any fabrication, alignment and systematic errors of the achromat directly affect the measurement. A closer look reveals that these errors largely originate from spherical aberration of the achromat. This aberration can be described by the 9th polynomial of the Zernike-Fringe decomposition: $Z_9 = 6 r^4 - 6 r^2 + 1$, with r denoting the radius of the surface.

Interferometer software usually provides for the analysis of the Zernike coefficients and it is thus possible to correct the interferogram for these coefficients. By subtracting the coefficient Z9, described above, from the interferogram, the residual systematic errors are reduced by more than one magnitude, thus leading to a measurement precision of PV < λ/10 covering the full range with 1 m < |R| < 350 m.

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[1] M.V. Mantravadi, Newton, Fizeau, and Haidinger interferometers, Optical Shop Testing, Daniel Malacara, sec. ed., pp. 1-50, John Wiley and Sons, New York (1992)

[2] J.-M. Asfour et al., Asphere testing with a Fizeau interferometer based on a combined computer-generated hologram, J. Opt. Soc. Am. A, vol. 23, 1, pp. 172-178, 2006

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Originally published in German in Photonik 2/2007