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Summary of high-accuracy aperture-area measurement capabilities at the NIST

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Abstract. The determination of the geometrical and effective area for optical-quality apertures is one of the fundamental sources of uncertainty in many radiometric and photometric measurements. The National Institute of Standards and Technology (NIST) has developed two non-contact instruments for measuring the area of these optical apertures. Some details of the instruments and their capabilities are presented. Both instruments can be used to measure the area of apertures with diameters ranging from 3.5 mm to 25 mm. The measurements using the absolute instrument result in $k = 2$ relative uncertainties ranging from 3×10^{-5} for 25 mm diameter apertures to 5×10^{-5} for 3.5 mm diameter apertures. The uncertainty depends to some extent on the quality of the edge and the diameter of the aperture. The measurements using the relative instrument result in $k = 2$ relative uncertainties ranging from 2×10^{-4} for 25 mm diameter apertures to 3×10^{-4} for 3.5 mm diameter apertures, assuming adequate optical-edge quality. For apertures with an edge of very poor quality, the difference between geometrical and effective area can be as high as 0.3 %. The increased uncertainty largely arises from scattering from the edge. Both instruments play a major role in the Consultative Committee for Photometry and Radiometry (CCPR) key comparison on aperture area, which began in 1999.

1. Introduction

As the total uncertainties of radiometric and photometric measurements continue to decrease [1], the role of aperture-area measurement is growing in importance. Two instruments have been developed at the NIST for these area measurements: (i) an absolute instrument capable of measuring aperture area with a relative uncertainty of less than 5×10^{-5} $(k = 2)$* for apertures in the range 3.5 mm to 25 mm diameter, depending on the overall quality of the edge; (ii) a flux-transfer instrument, optimized to measure aperture area relative to an aperture of known area with relative uncertainties in the range 3×10^{-4} to 4×10^{-4}, depending on aperture size.

2. Absolute area-measuring instrument

The absolute instrument [2, 3], shown in Figure 1, measures radii relative to an arbitrary point. The radii are then fitted to a circle and ellipse for calculation of the area. The instrument consists of a heavy granite structure supporting a microscope/CCD (charge-coupled-device) camera system. The granite structure is attached to an optical table that is isolated in order to eliminate vibration transmitted through the structure of the building. The structure consists of an inverted "T" with a planar, air-bearing-supported carrier on the horizontal surface and a high-precision optical microscope with a long working distance mounted on an air-bearing slide on the vertical surface. The stage is moved using a linear servo-motor system in the horizontal or x-y plane and a lead-screw in the vertical or z axis. The z-axis motion is controlled by a servo-motor with a chrome-on-glass scale for position feedback. The x-y stage is very accurately positioned using a two-pass-dual-frequency laser-interferometer system. The measurement is directly linked to the International System of Units through the laser interferometer. The illumination is provided by a custom-made Köhler illuminator system. The aperture under test is mounted at the top of the hollow carrier in the same plane as the laser-interferometer beam.

The data produced are fitted to both a circle and an ellipse. By comparing the residuals for both fits, it can be determined whether an aperture is round or elliptical. A third algorithm, the comprehensive method, may be used for apertures that are pseudo-round (neither circular nor elliptical). The material from which the aperture is fabricated is not a factor in this measurement, and the edge construction is generally insignificant as long as the contour is relatively smooth. Edge quality is only a factor if the edge has irregular discontinuities.

Apertures have been fabricated using various processes for testing the capabilities of the instrument.

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*Note: all uncertainties are expressed with coverage factor $k = 2$.

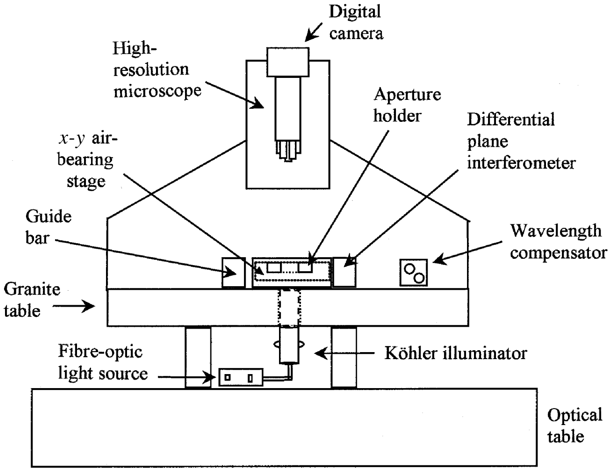

Figure 1. General layout of the absolute instrument.

One type of aperture is diamond-turned and based on a gold-plated copper substrate. The diamond-turning machine [4] on which these apertures were fabricated is known to be capable of turning a circle to within 30 nm [5] of a perfect circle. The residuals from the circle fit indicate agreement with the circularity commensurate with the diamond-turning process. Between 45 min and 2 h is required to measure one aperture, depending on the number of edge points chosen.

3. Relative area-measuring instrument

The relative instrument [3, 6], shown in Figure 2, determines aperture area by the flux-transfer method. The instrument consists of a custom-built sphere-based illuminator, light trap, aperture-positioning system, and flux-collection system. The illuminator consists of a 250 W quartz-halogen lamp, commercial lamp housing, liquid-water radiation filter to limit the wavelength to less than 1 µm, focusing lens, and custom-designed coaxial sphere with a high-precision low-temperature-coefficient aperture at the output port. The light trap is actually an enclosed room lined with a highly diffuse and light-absorbing material, minimizing any adverse effects from scattered light originating from system components in front of the aperture mounting area.

Up to seven apertures to be tested, together with a standard aperture of known area, are mounted in a wheel positioned by a servo system. The flux passing through the aperture in the test position is collected by a 100 mm diameter spherical mirror and focused on a 10 mm diameter silicon detector. The test optics is enclosed in a large light-tight box covered on the inside with the same absorbing black material as used in the light trap. A monitor detector compensates for slight fluctuations of the lamp. The area is calculated from the ratio of the fluxes through the standard and test apertures, together with the known area of the standard aperture using the relationship

$$A_{\text{test}}/A_{\text{standard}} = V_{\text{test}}/V_{\text{standard}}, \quad (1)$$

where A_{test} is the unknown aperture area, A_{standard} the area of the known standard aperture, V_{test} the voltage produced by the flux through the unknown aperture, and V_{standard} the flux through the standard aperture.

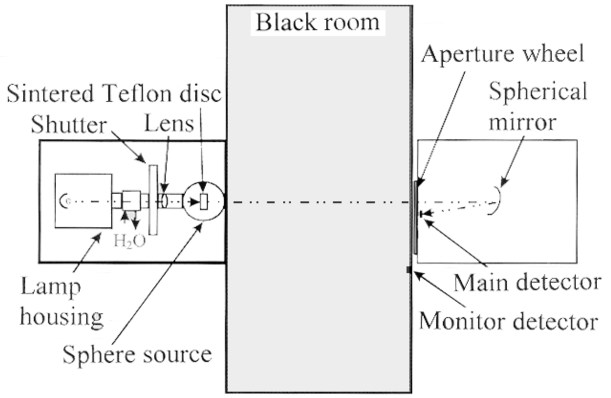

Figure 2. General layout of the relative instrument.

The result from the relative instrument is an effective area dependent on the material and the quality of the aperture edge, and the optical proportions of the measuring instrument. The results of the relative instrument are corrected for diffraction and scatter relative to a nearly round aperture with excellent edge quality. The resulting calculated area is nearly equal to the geometrical area of the aperture. The measurement of seven unknown apertures only requires 20 min.

4. Aperture-area measurement capabilities

The absolute instrument is capable of measuring the area of 3.5 mm apertures with a total relative uncertainty of less than 5×10^{-5} and 25 mm diameter apertures with a total relative uncertainty of less than 3×10^{-5}. The major components of the measurement uncertainty arise from the accuracy of the positioning system and the edge-detection capability.

The accuracy of the instrument has been tested using several different methods. Employing techniques developed by the semiconductor industry, a pair of 100 mm by 100 mm chrome-on-glass grid plates were produced along with two smaller artefacts used to check the calculated accuracy of the instrument. The grid plate is divided by lines spaced on 10 µm centres with a positional uncertainty of 34 nm anywhere on the plate. The accuracy was also checked against measurements made with a coordinate-measuring machine (CMM) utilizing a "touch" probe and apertures each having a land. The uncertainties of the measurements with the CMM were of the order of 1 µm. The areas measured by the absolute instrument were always comparable to the areas measured with the touch probe to within the uncertainties of the CMM. Although not an absolute check, the touch probe provides supporting data. In addition, some informal measurements have been made with another international laboratory and other CMM machines, which all show agreement within the uncertainty.

The relative instrument measures transmitted flux. The relative maximum root-mean-square deviation among twenty measurements is 5×10^{-5}. The overall accuracy is difficult to quantify. Each aperture tested has properties that affect the measurement. Systematic effects such as diffraction and scatter can be accounted for, but these corrections change with aperture size, edge quality, and to some degree with type of material. When measuring the same type of aperture, total relative uncertainties of 10^{-4} for 25 mm diameter apertures and 3×10^{-4} for 3.5 mm diameter apertures are typical after correction for diffraction.

The relative instrument was designed to measure rapidly the area of large numbers of similar apertures. The data allow calculation of the geometrical area as well as providing details of diffraction and scatter, which together can be used to help define how to use these apertures in a real optical system at low levels of uncertainty.

5. Possible problems associated with using aperture area in instruments

When using apertures in optical instruments, except when placed very near the detector surface, diffraction and scatter can be sources of systematic uncertainty that are difficult to quantify. The diffraction may be accounted for with reasonable uncertainty, but the light scattering is much more difficult to quantify because it depends on the quality of the aperture edge: in general, there will be a difference between the total flux transfer in the aperture-area measuring instrument and that in the final optical instrument that makes use of the aperture. It may be possible to quantify the diffraction and scatter in addition to the aperture area, with only a small degradation in the overall uncertainty, by using data from both instruments. More work is required in this area to verify this concept.

6. CCPR aperture-area comparison

The CCPR supplementary comparison on aperture area, reference CCPR-S2, is currently under way, with the NIST as lead organization. Both of the instruments described here will play a role in the comparison. Each time the aperture set returns to the NIST, all of the apertures will be remeasured on the absolute instrument and occasionally on the relative instrument. When the comparison is complete, the results will include seven laboratories and more than eight data sets from the NIST instruments.

7. Conclusions

Aperture area at the NIST is measured to extremely high accuracy for round apertures with total relative uncertainties of 3×10^{-5} to 5×10^{-5} using the absolute instrument described. Higher-speed measurements will be made using the relative instrument with total relative uncertainties of 10^{-4} to 3×10^{-4}. For an irregularly shaped aperture, its contribution to the overall uncertainty could be misleading, depending on the aperture size, edge quality, and material. Using the relative instrument, information about diffraction and scatter may be obtained that cannot be obtained from the absolute instrument. These additional data may be useful in determining the effective, rather than the geometrical, area for a given optical arrangement. More research is being conducted to understand better how these effects may be minimized or accounted for in practice.

References

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