High-accuracy aperture-area measurement facilities at the National Institute of Standards and Technology

Joel B. Fowler, R. S. Durvasula and A. C. Parr

Abstract. The uncertainty in the measurement of aperture area can limit high-accuracy radiometric and photometric measurements. Relative total uncertainties in some measurements have now been determined at or below the 0.1 % level, making substantially smaller aperture-area measurement uncertainties necessary. The National Institute of Standards and Technology (NIST) has recently implemented an absolute aperture-area measurement facility and a relative aperture-area measurement facility; the two facilities together are designed to determine aperture areas with low uncertainty. The absolute instrument measures the aperture-area using optical edge detection, along with high-precision positioning of the optical edge relative to the sensor, resulting in an expected relative combined standard uncertainty of less than 10^{-4}. The relative instrument uses optical flux transfer to compare aperture areas and also has an expected relative combined standard uncertainty of less than 10^{-4}. The absolute instrument will be used to measure the area of standard apertures for use with the relative instrument.

1. Introduction

To be certain that aperture-area measurement is not the limiting factor in the precision of radiometric and photometric measurements [1], an aperture-area measurement with a total relative combined standard uncertainty of the order of 10^{-4} or less is required. At the National Institute of Standards and Technology (NIST), a new facility comprising two separate but related instruments has been constructed that can be used to measure aperture area with combined standard relative uncertainties of less than 10^{-4}, depending on aperture size.

The first instrument, which measures absolute aperture area, utilizes a high-quality microscope with long-working-distance objectives. The microscope is mounted on a granite support structure. A single-level stage, with X and Y movement on the same plane, is supported by the granite structure beneath the microscope assembly. The X and Y position of the stage is referenced to a two-pass laser interferometer with a combined standard uncertainty in position of less than 50 nm. The positioning system is computer controlled. This instrument will have the capability to measure aperture area to a total combined standard uncertainty of 10^{-4} or less for apertures ranging from 2 mm to 30 mm in diameter, and will be used principally to measure standard apertures for use with a flux-transfer instrument described below.

Joel B. Fowler and A. C. Parr: National Institute of Standards and Technology, Gaithersburg, MD 20899, USA.
R. S. Durvasula: Tufts University, Medford, MA 02155, USA.

The second instrument determines the radiometric flux through an aperture. Using the principle that the radiometric flux passing through an aperture is directly proportional to its area, the area of an aperture of unknown area is determined in terms of the area of a standard aperture of known area. In other words, the ratio of the radiometric flux through the two apertures is equal to the ratio of the areas.

2. Absolute instrument

The absolute instrument, a photograph of which is shown in Figure 1 and a schematic diagram in Figure 2, comprises a precision microscope, a granite support structure, and a single-level, air-bearing-supported stage, with X and Y movement on the same plane. The stage is positioned using a linear servo-positioning system with feedback control; the positional measurement is referenced to a compensated, two-pass, laser interferometer system, which references the measured positions to the wavelength of the laser. The entire apparatus is contained inside a class-10 000, soft-walled clean room.

The granite support structure is shaped in the form of an inverted T. The microscope is mounted on a servo-positioned air-bearing stage which is attached to the vertical part of the inverted T. The microscope is equipped with long-working-distance, short-focus, high-power objectives with magnifying powers of 10, 20, 50, 80, and 100. The aperture edge is imaged onto a 10-bit, digital charge-coupled-device (CCD) sensor system. The stage is mounted beneath the microscope and is supported on a cushion of air. There is no

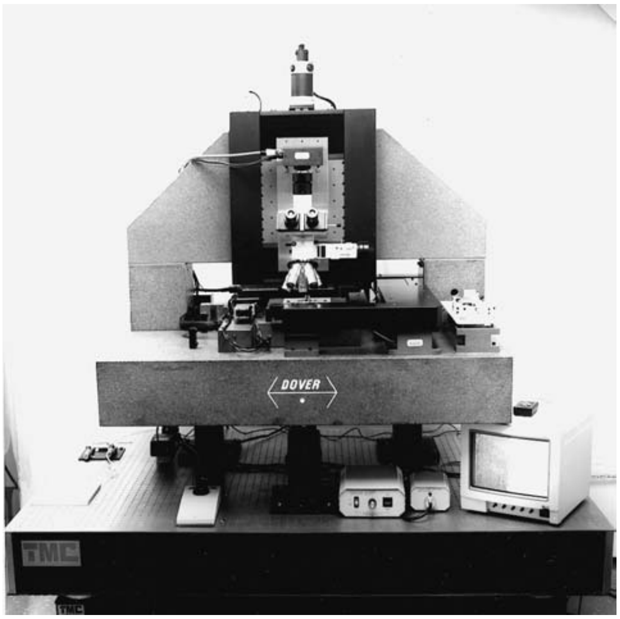

Figure 1. Photograph of the absolute aperture-area measurement instrument, showing the granite support structure, microscope, CCD camera, stage, and laser interferometer.

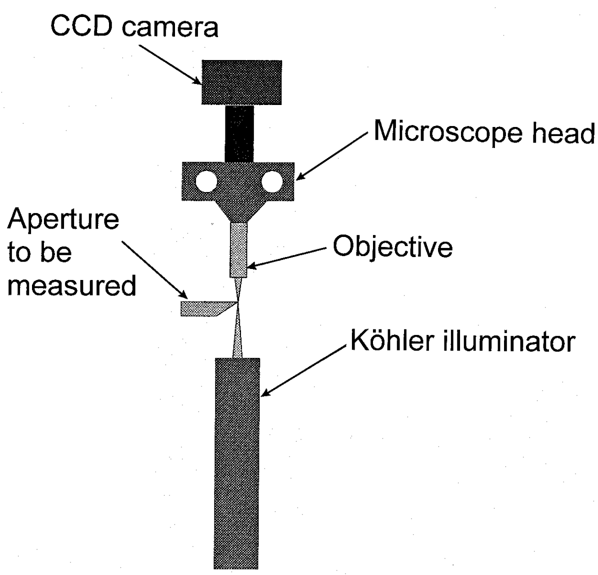

Figure 2. Schematic diagram of the absolute instrument.

physical contact between the stage and any other parts. The entire measurement process is controlled by a computer.

The aperture is positioned on the stage below the microscope and illuminated from beneath using a variable-aperture, Köhler illuminator. The numerical aperture of the microscope is matched to the numerical aperture of the Köhler illuminator. Matching of the numerical apertures decreases diffraction effects, increases the optical efficiency, and provides a uniform and diffuse optical field at the object plane.

To measure the area of an aperture, the operator places it in the holder on the stage, manually positions the aperture edge approximately in the centre of the field-of-view of the CCD sensor using the joystick control and starts the measurement process. This manual positioning procedure is rapid and is used only to save time.

The next step, determining the optimal focal location of the camera for viewing the aperture edge, is achieved using the gradient magnitude maximization method [2] (commonly referred to as the Tenengrad method) across the aperture edge at discrete locations along the optical axis. In order to minimize the number of locations to be tested within a given possible range, a Fibonacci algorithm [3] is used to optimize the search.

The stage is then translated so that the edge segments along the aperture profile are imaged onto the CCD sensor at discrete angular increments chosen by the operator. At each stage position, an edge-detection algorithm determines the location of the edge across a scan line of pixels. The edge-detection algorithm assumes a perfectly incoherent illumination model; for a given set of transitional pixels across the aperture edge, the sub-pixel edge location is determined by linear interpolation of the mid-grey-level intensity between the two extremes. Once these edge locations are determined for each angular increment, a least-squares-fitting routine [4] is used to determine the geometric parameters of the aperture profile.

3. Flux-transfer instrument

The flux-transfer instrument, which is shown in Figure 3, is similar to an instrument built at the NIST in 1995 [5]. The instrument has four major components: control room, source room, light trap room, and measurement room. The control room includes the control computer, the supporting electronics for the rest of the instrumentation, and an assembly area. The instrument is completely automated; the operator is required only

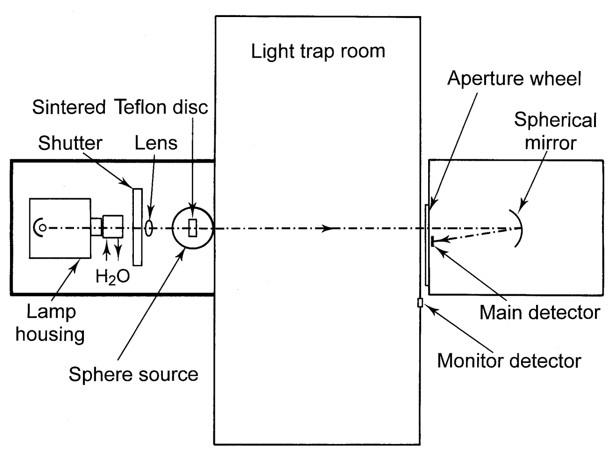

Figure 3. Schematic diagram of the flux-transfer instrument, showing the system layout.

to insert the apertures into a rotating aperture holder and to initiate the measurement procedure.

The source room contains two optical benches mounted one on top of the other, with the light source mounted on the upper table. Two benches were used to increase the mass in order to damp any vibrations and to prevent relative movement between the optical components. The source consists of a 250 W quartz-halogen lamp mounted in a lamp housing, a liquid-water optical filter to absorb wavelengths above 1 µm, an 88 mm focal-length lens, a shutter to permit background measurements and a specially constructed integrating-sphere source to produce uniform Lambertian illumination at the test position. The lamp housing traps unwanted radiation; the sphere source is coaxial with the lamp, filter, and lens. The focal length of the lens was chosen so as to provide an image small enough to underfill the inlet port of the sphere source.

The inlet and outlet ports of the integrating sphere are aligned coaxially. The inlet port, which measures 8 mm in diameter, is located in the centre of the front half of the sphere, and the outlet port, which measures 8 mm in diameter, is located in the centre of the rear half of the sphere. A sintered Teflon disc supported on thin stainless-steel wires is positioned in the centre of the sphere between the inlet and the outlet ports. The disc is 35 mm in diameter and 25 mm thick, with a metal disc moulded into the centre to eliminate direct transmission of light from the inlet port to the outlet port. The outlet port is fitted with an 8 mm diameter precision aperture with a low thermal coefficient of expansion.

The sphere source is mounted through the centre of one wall of the light trap room, which is covered on the inside with a diffuse, optical-absorbing material. The covering material is UltraPol V (product of the Rippey Corp., El Dorado, CA), which was originally designed for polishing integrated circuit wafers. This material has a directional hemispherical reflectance of less than 1.5 % in the visible region. The light trap room is a large compartment, 3.1 m wide × 2.9 m high × 2.3 m deep designed to minimize scattered light through the aperture under test. To reduce scattered light from the room walls to a minimum, the height and width of the room would ideally be infinite but are of course dictated by the finite space available. The optical axis of the source is coaxial with the aperture-holding device, which is centred in the back wall of the light trap. The distance between the source aperture and the aperture under test is 2.315 m. At this distance the source approximates a point source. The uncertainty in the source-to-aperture distance is 0.1 mm when changing from one aperture to another.

The measurement room contains the aperture-holding device and a light-tight box containing the collecting mirror and photodiode. The aperture-holding device is a circular wheel 356 mm in diameter with eight test positions spaced equally around the circumference. The apertures are held in the wheel with magnetic aperture holders indexed to the surface of the wheel. The wheel assembly is precision machined to achieve an uncertainty in position at the outer edge of less than 0.1 mm in any of the three axes. The wheel is positioned using a servo-motor system to achieve a rotational uncertainty of less than 5′. The flux through each aperture in the test position is collected on a spherical mirror 200 mm in diameter with a 0.5 m radius; this flux is then focused on to a photodiode. The mirror is double-coated with a protected silver coating, has no pinholes in the central 50 mm diameter and has a surface reflectance uniformity of 0.9999 % or better in the central 50 mm diameter. The 1 mm diameter focused spot is collected by a Hamamatsu S-1228 photodiode. The spatial response uniformity of the diode is 0.9999 % or better in a selected 1.5 mm diameter area, which is not necessarily the central area of the diode. Departure from response linearity of the diode/amplifier combination as measured using flux superposition methods is less than 0.005 % and does not contribute significantly to the overall uncertainty of the measurement. The mirror and the diode are enclosed in a light-tight box covered on the inside with the same material as the light trap room to minimize stray light. A special, differential-current-to-voltage converter was designed in order to minimize synchronous noise sources such as 60 Hz line noise.

4. Results

Preliminary data for the absolute measurement indicate that aperture-area measurements may be made with less than 10^{-4} relative standard uncertainty; this result was informally verified by comparison with an aperture which was measured at another national laboratory with a relative combined standard uncertainty of less than 10^{-4}. Ultimately, the factors which constrain the overall system accuracy include (but are not limited to): (i) the accuracy to which the system magnification can be determined; (ii) the accuracy to which the XY stage can be positioned; (iii) the ability to model the degree of coherence of the light source accurately; and (iv) the number of discrete edge points used in the circle-fitting routine.

Current measurements using the flux-transfer instrument are limited by the uncertainty in the area of the standard aperture. The area of the standard aperture being used is known to within 3×10^{-4} relative combined standard uncertainty. An aperture to replace this one is currently being fabricated using diamond-turning techniques. The area of the new standard aperture will be measured using the absolute instrument.

The absolute instrument is undergoing procedures for characterization and optimization. Both instruments are expected to be fully operational by the end of 1998. Details of both instruments and their capabilities will be presented in future publications.

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Note. References are made to certain materials and products in this paper to specify adequately the experimental procedures involved. These references do not imply recommendation or endorsement by the NIST, nor do they imply that these products are the best for the purpose specified.

References

1. Johnson B. Carol, Cromer C. L., Saunders R. D., Eppledauer G., Fowler J., Sapritsky V. I., Dezsi G., *Metrologia*, 1993, **30**, 309-315.
2. Krokotov E., Focusing, *Int. J. of Computer Vision*, 1987, **1**(3), 223-227.
3. Beveridge G., Schechter R., *Optimization: Theory and Practice*, New York, McGraw-Hill, 1970.
4. Joseph S., Unbiased Least Squares Fitting of Circular Arcs, *CVGIP: Graphical Models and Image Processing*, 1994, **56**(5), 424-432.
5. Fowler J., Dezsi G., *J. Res. Natl. Inst. Stand. Technol.*, 1995, **100**, 277.